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THE METEOROLOGICAL HISTORY OF THE NEW ENGLAND HURRICANE OF SEPT. 21, 1938

By CHARLES H. PIERCE

[Weather Bureau, Washington, D. C., July 1939.]

A general account of the damaging hurricane that swept northward through New England on September 21, 1938, was given by Ivan R. Tannehill in the September 1938, issue of the MONTHLY WEATHER REVIEW. The purpose of the present discussion is to investigate the details of the structure and the motion of the storm as shown from surface and upper-air observations within or near it; in these respects the cyclone was exceptional owing to its passage into a region where frequent observations from a relatively dense network of reporting stations could be obtained and where a certain amount of aerological material was available. This made it possible to study in greater detail than has been possible in previous hurricanes such matters as the action with extra-tropical fronts, the winds and temperatures aloft in the vicinity of the storm and the details of a peculiar secondary cyclonic area near the low center. Much of the information appears useful in developing the theory and actual descriptive knowledge of tropical cyclones in general. The series of detailed maps of the storm is reproduced here in full because it is believed that such a complete series is unique in hurricane studies, and because the charts tell much that has been left unsaid in the text.

This storm has been ranked as "America's costliest disaster." The exact property damage cannot, of course, be ascertained; but according to the Travelers Insurance Co. of Hartford, Conn., the surveys by the insurance trade and others justify the acceptance of an estimate of at least $400,000,000, as compared with the commonly accepted figures of $350,000,000 loss in the San Francisco earthquake and fire of 1906 and $200,000,000 in the Chicago fire in 1871. The hurricane at Galveston, Tex., in 1900 took 6,000 lives, as against only 680 in the 1938 storm; but the property damage in the former was but $30,000,000. About 95 percent of the hurricane damage in New England was not covered by insurance.

The actual history of the hurricane goes back to some time before September 13, when it was noticeable in the region of the Cape Verde Islands. However, it was not until September 16 that the meteorological conditions began to operate in the western Atlantic and eastern United States that determined the peculiar destiny of the storm from that date through the 22d. Therefore, the present discussion will start with conditions that existed on September 16 and extended through the 22d. An outline of the circulation aloft, especially on isentropic surfaces, will first be given.

On September 16, the hurricane was located approximately at latitude 23° N. and longitude 53° W. In referring to figures 1a and 1b, which show the winds at 10,000 and 6,000 feet on this date, it will be noted that there was a very strong anticyclonic circulation the axis of which extended east and west at about 25° N., with the western tip over Florida. The isentropic chart, figure 1c, shows that a moist tongue was streaming around the western periphery of this strong anticyclone. All of the aerological stations on the eastern seaboard showed high moisture content, while the air west of the Appalachians was dry. During the 16th and on the 17th, a warm anticyclone was developing over the northeastern part of the country. This is shown in the upper air circulation at 6,000 feet at 4 a. m. on September 17 (fig. 2b). At the same time the axis of the strong southern high was shifting northward, as is indicated by Bermuda's winds on the 6,000 and 10,000-foot upper-air maps (figs. 2a and 2b) for September 17. The isentropic chart of September 17 (fig. 2c) shows that there is a branch of the moist tongue making its way north-northeast up the North Atlantic coast. It was this branch that became the main moist tongue and that caused the heavy rainfall in New England during the next 5 days. The synoptic chart (fig. 8) for September 17, 7:30 a. m., shows a wave development over southeastern Virginia. This and several other waves along the front brought the warm air at the ground farther and farther to the northeast.

By the 18th (Fig. 3a), the warm anticyclone became well established north of Bermuda, with a ridge extending south-southwestward along the coast. Over New England, the winds aloft which had been from west-southwest on the 16th, now became south-southwest. Although we have no upper-air data from Bermuda, the surface wind which was southwest on the 16th shifted to east by the 18th.

While these changes were taking place, a deep LOW at the surface and aloft was developing just west of Chicago which accentuated this strong south-southwest flow. This LOW shows up on the 10,000-foot map at Chicago, which had a pressure fall of 0.2 inch in 24 hours. The LOW at the surface occluded and filled over Michigan on September 18, but the cold air imported during the occlusion maintained a deep LOW aloft. Thus between the cold LOW centered in the vicinity of Michigan and the warm anticyclone centered north of Bermuda, the conditions were ideal for a rapid transportation of warm moist air from the south along the east coast.

On figure 3a, showing the upper-air circulation in the Tropics on the 18th, it will be noted that, as the hurricane approached the West Indies, the winds became strong northeast. In connection with this, on the isentropic chart (fig. 3c) there was a marked dry tongue drawn in from northern latitudes which appeared very distinctly over St. Thomas.

On September 19 the hurricane was located at 24° N. and 70° W. The upper-air winds indicate a pronounced trough in this region (fig. 4a). With the shift of wind into

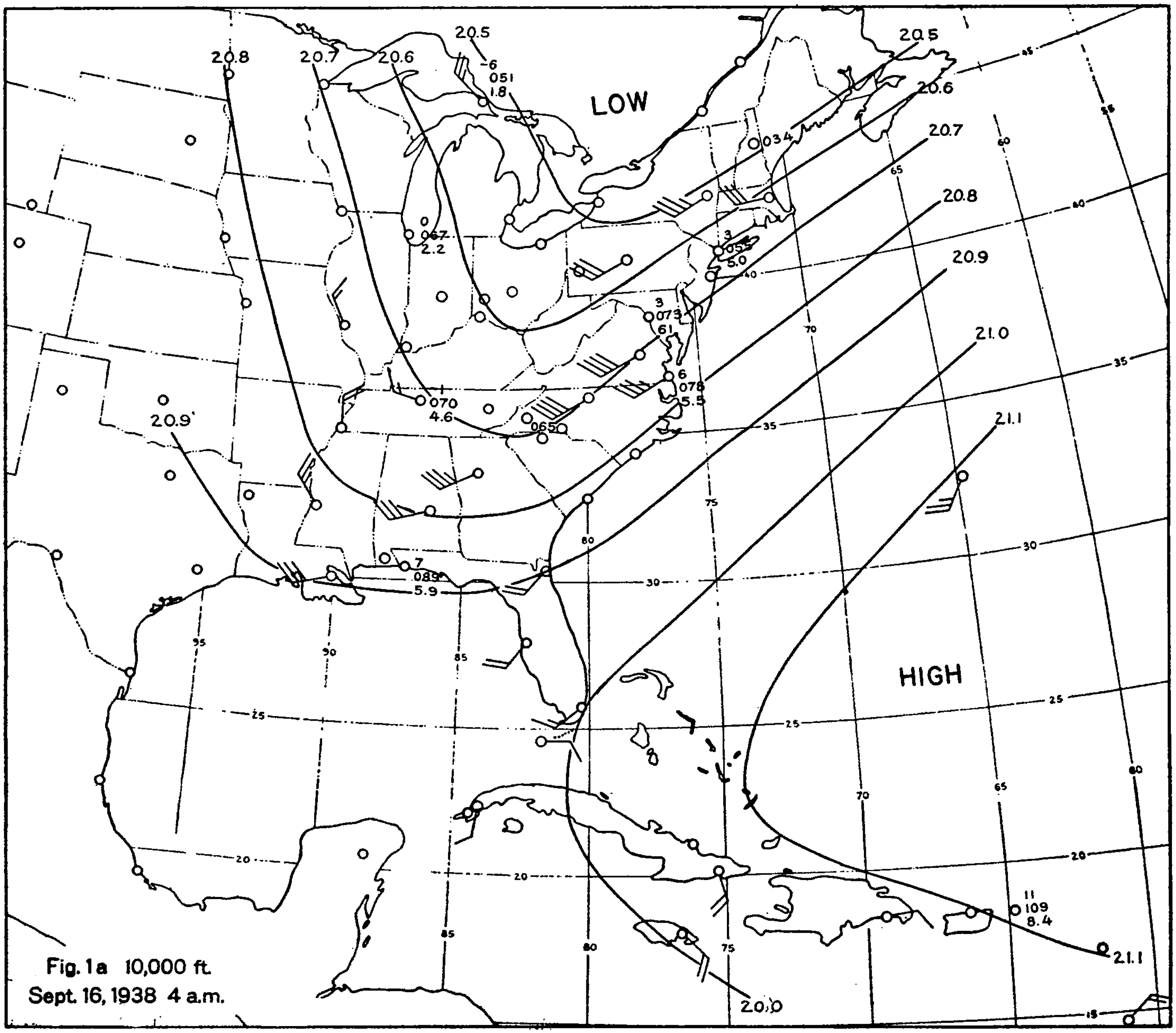

Fig. 1a 10,000 ft.
Sept. 16, 1938 4 a.m.

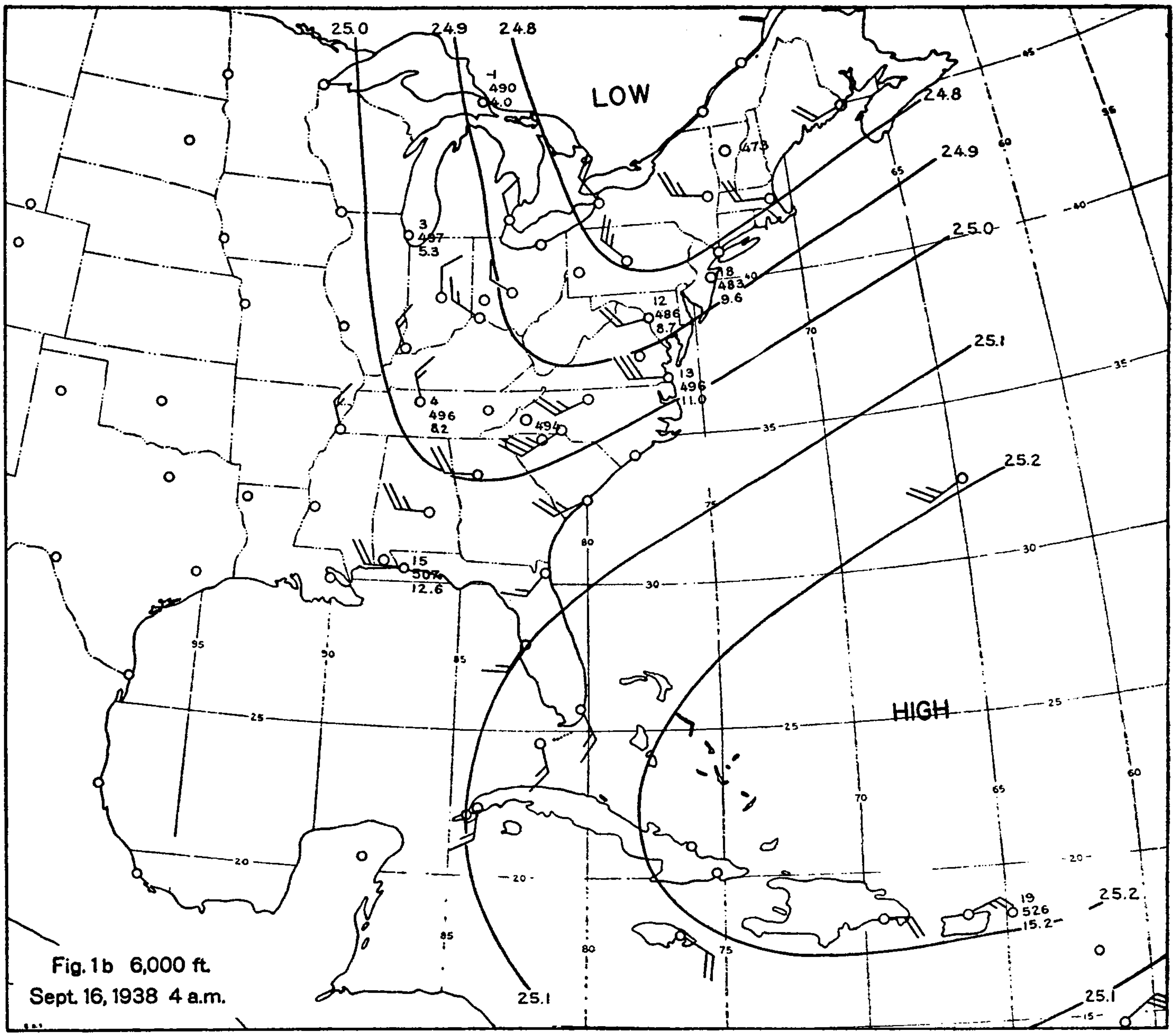
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Fig. 1b 6,000 ft.
Sept. 16, 1938 4 a.m.

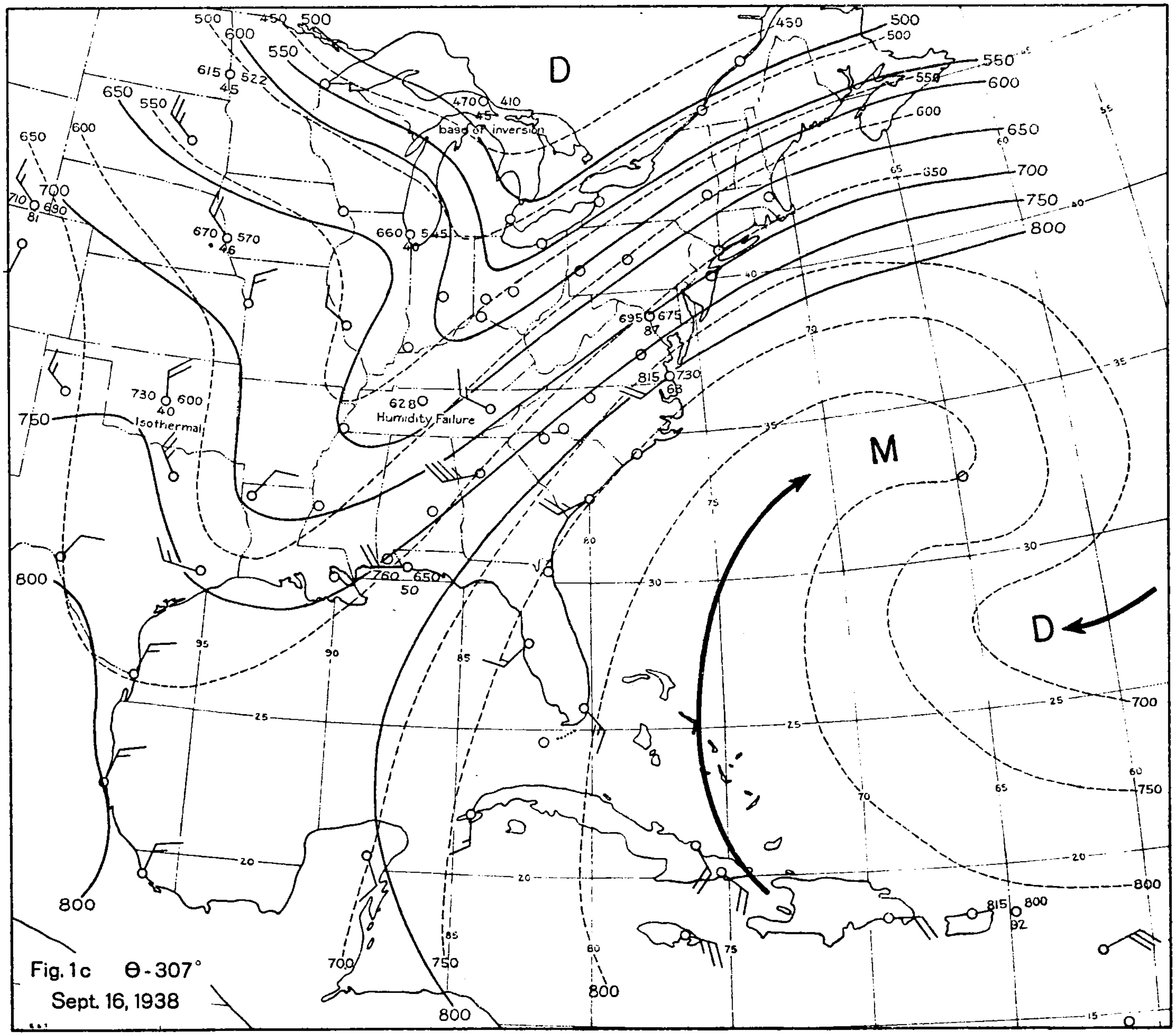


Fig. 1c Θ-307°
Sept. 16, 1938

the southeast at St. Thomas, a considerable increase in moisture was noted at this station. This was produced by the moist, more unstable air drawn in by the hurricane from the doldrum regions. (See fig. 4c).

CONDITIONS IN THE EASTERN UNITED STATES

Over the eastern part of the United States, cold air was being imported from the northwest at Chicago and Nashville and warming was continuing along the eastern coast. This produced an even stronger pressure gradient than was found on the 18th. Winds in the upper air were all force 6 and 7 from the south-southwest.

The steep temperature gradient is also shown on the isentropic chart for the 19th (fig. 4c). It will be noted that the slope of the surface is relatively flat in the extreme east, but becomes very steep westward from Ohio. This agrees with the position of the eastward-moving cold front associated with the stationary LOW over Michigan. With the cold air so deep, the cold front was naturally quite steep. It is the author's belief that this cold front had much to do with maintaining the energy of the hurricane after the morning of the 21st.

As the secondary cold front moved eastward, steepening of the isentropic slopes along the coast resulted. This caused rapid lifting of the moist air to the condensation level, to produce heavy rainfall, especially over New England, on the 20th. On the isentropic chart (fig. 5c) it is noted that the 307° surface has a very steep slope, with the moist tongue, with strong south-southwest winds still maintained across New England, extending from the Tropics. However, dry air from the northwest was flowing into the southeastern section of the country. On this date, the hurricane, still surrounded entirely by tropical Atlantic air, was located at 27° N. and 75° W. That the circulation of the hurricane was maintained aloft is shown on figure 5a by the north-northwest wind at Miami and the south wind at Charleston.

In the northeast the cold air seemed to be definitely pushing eastward now. In fact, Mount Washington, which had been in the tropical air for several days, was now in the polar air. The front separating tropical air from polar air was also followed by the steep secondary front from the west, which should have given it added momentum. If this were true, the frontal trough should have been out over the ocean by the 21st, and the hurricane would have moved to the northeast along this trough. The apparent eastward push of the cold air did not last, so that by 7:30 p. m. of the 20th the tropical air had pushed westward again in New England; Mount Washington observed a south wind force 4 Beaufort and a temperature of 54. (Compare Mount Washington on figures 9 and 10.) C. F. Brooks at Blue Hill Observatory also noted that the movement of the upper clouds on the 21st was from the south. Farther south, however, the cold air continued to push eastward. This is indicated by the autographic records at Hatteras, which showed a wind shift from southwest to northwest and a sudden drop in temperature. Within the circulation aloft, as is shown on the 6,000-foot upper-air chart of 4 p. m. (fig. 5b), there seems to be a trough forming between the cold LOW near Cleveland and the LOW formed by the hurricane. However, two separate centers are still maintained.

The situation at this point may be stated briefly as follows: The subtropic anticyclone is displaced quite far to the north with a quasi-stationary front running from Maine south-southwest to Virginia. To the east of this front is very warm moist air and to the west there has been an importation of a deep cold-air mass. The hurricane which was previously surrounded entirely by tropical maritime air is now approaching a region where there are two distinct air masses.

FRONTS IN THE HURRICANE

During the night of the 20th, the hurricane passed through a transitory stage. It changed from a tropical to an extra-tropical storm—an extra-tropical storm, however, that maintained hurricane intensity.

Like most other extra-tropical storms, this one had a definite system of fronts. On the face of it, this sounds like an absurd statement, because meteorologists think of a deep circular LOW as one that contains no fronts. There may be those that have occluded and "wound up" their fronts and therefore are entirely surrounded by polar air, or there may be hurricanes that are surrounded by tropical air. However, when the hurricane moves into a region where there is a definite front with cold dense air to the west or north, then the tropical air of the hurricane is going to ride up over the dome of cold air to the north of the LOW center, and the circulation will cause the cold air to blow in from the west in the southern part of the LOW. Now, if the hurricane continued to move slowly, then the cold air would soon sweep around the center and occlude the tropical air. This would result probably in the filling of the hurricane. In the case of September 21, however, it must be remembered that the acceleration of the storm was extremely rapid, so that it was traveling close to 70 miles per hour off the New Jersey coast, which meant that it was traveling only slightly more slowly than the velocities of the particles of air within the storm. Therefore, the cold air did not have time to sweep around the center.

Let us consider what will happen to a distinct front, the southern end of which is being approached by a hurricane. According to all writers [1] the hurricane moves so that the anticyclone will be on the right. This means that, if there is a well defined trough between the Bermuda HIGH and the HIGH to the west, the hurricane will move up the eastern side of this trough. If there is a sharp front in this trough, the front first will move westward as a warm front as the winds increase in velocity from the east. If gradient winds existed, the front would naturally keep moving around the hurricane. However, this does not happen because there is a frictional effect to take into account. This frictional effect causes the winds to flow across the isobars at a certain angle, depending on the pressure gradient and the roughness of the surface.

A close approximation to this angle can be determined from Rossby's and Montgomery's data.[2] First we must determine the roughness parameter over the ocean. The expression for this is $z_0=s\epsilon$ where s is a nondimensional factor, and ϵ is the roughness element. Prandt [3] suggests a tentative value of 1/30 for s. Wüst [4] states that the roughness parameter (z_0) for the Baltic is between 3.2 and 4 centimeters. However, in dealing with the hurricane, we can safely assume that the roughness element, ϵ, is at least 3 meters; therefore, z would be one-thirtieth of this or 10 centimeters.

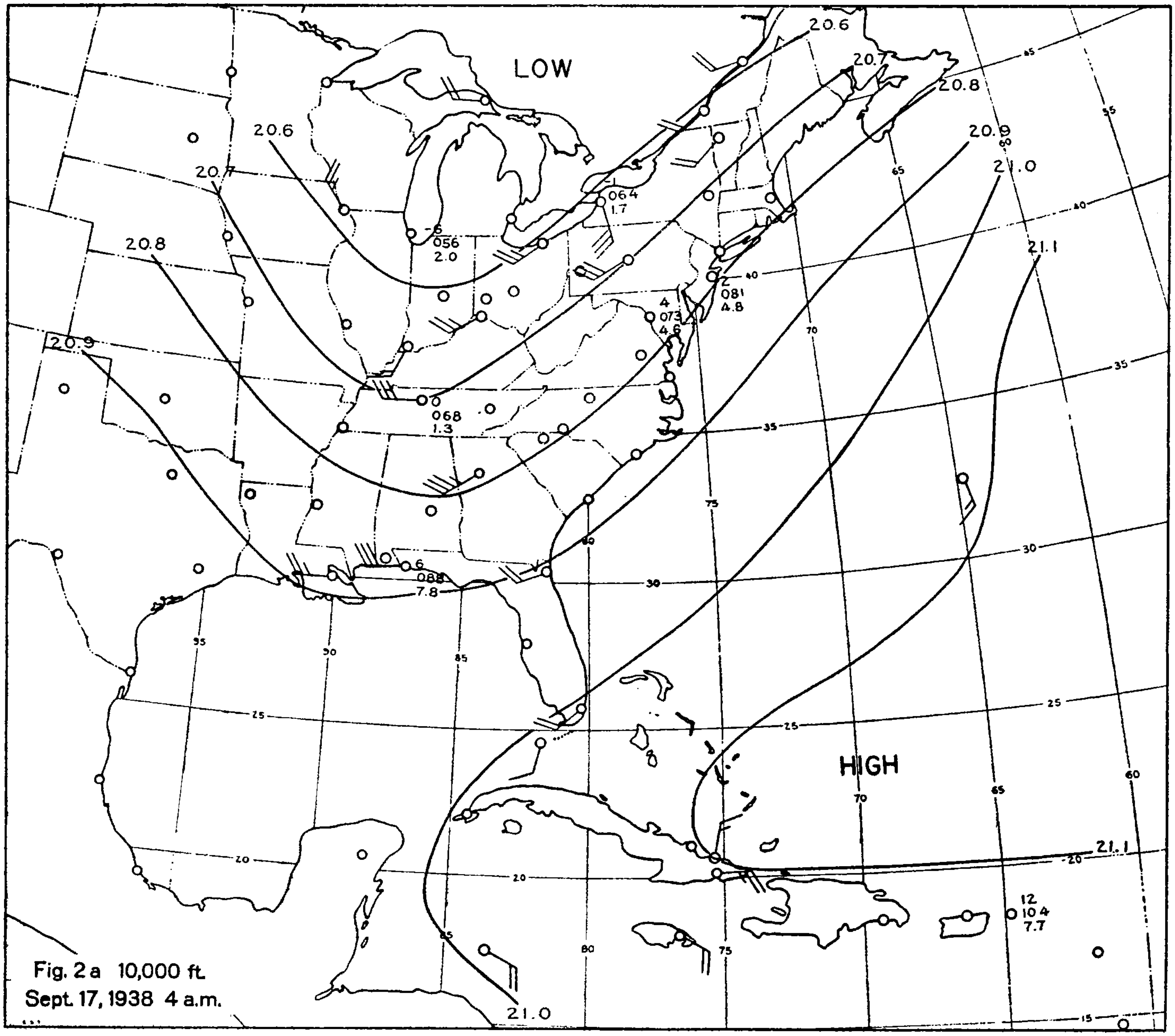
The wind speeds in the hurricane averaged about 25 meters per second. Referring to figure 8 on page 18 in Rossby's and Montgomery's paper, we see that the angle at which the winds would flow across the isobars at this

[1] Especially Mitchell, C. L. West Indian Hurricanes and other Tropical Storms of the North Atlantic Ocean, MONTHLY WEATHER REVIEW SUPPLEMENT No. 24.

[2] Rossby, C. G., and Montgomery, R. B. The Layer of Frictional Influence in Wind and Ocean Currents, p. 5, *Papers in Physical Oceanography and Meteorology*, published by Massachusetts Institute of Technology and Woods Hole Oceanographic Institution.

[3] *Ibid*, p. 5.

[4] *Ibid*, p. 19.


LOW
HIGH
20.6
20.7
20.8
20.9
21.0
21.1
Fig. 2a 10,000 ft.
Sept. 17, 1938 4 a.m.

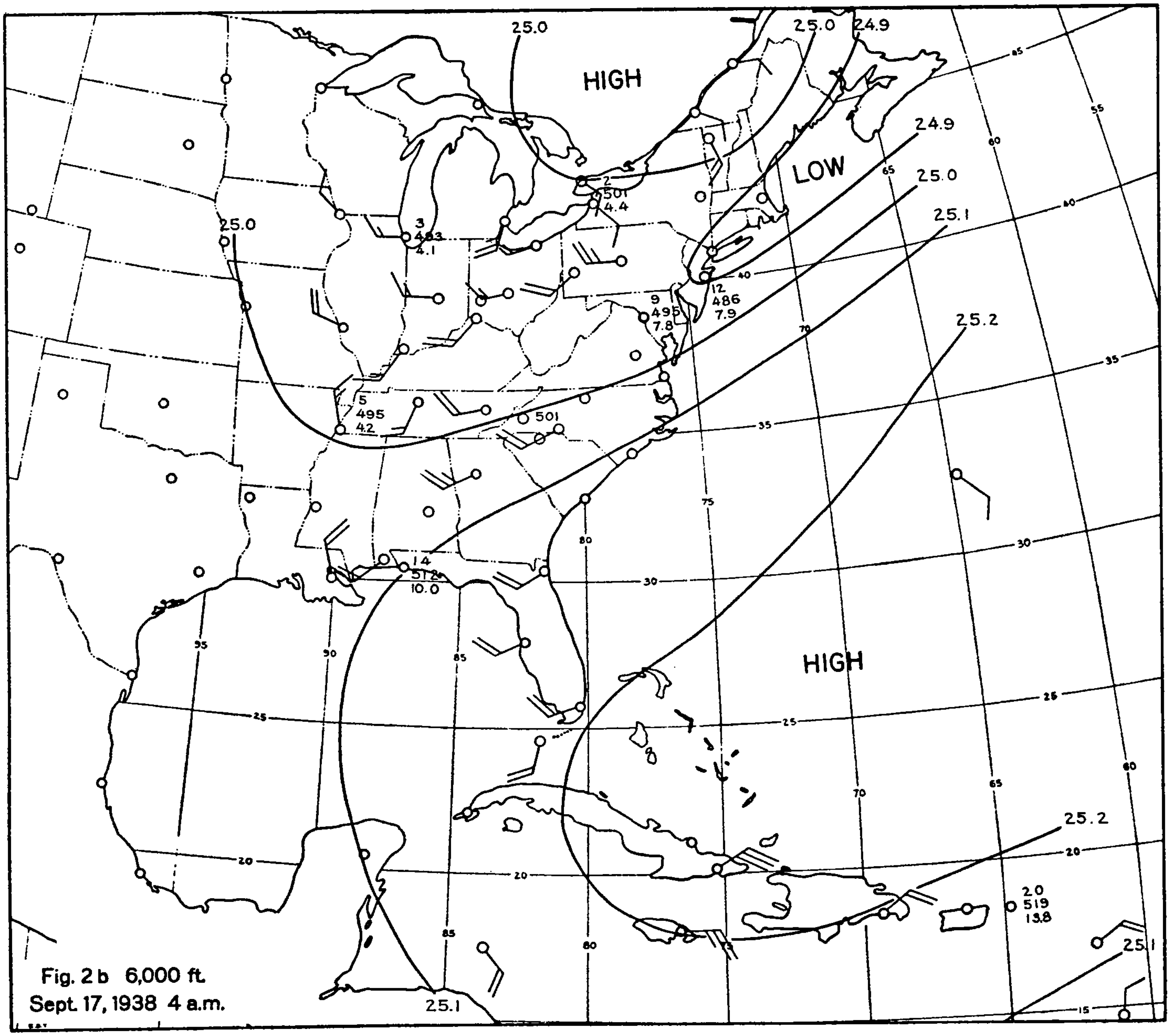


Fig. 2 b 6,000 ft.
Sept. 17, 1938 4 a.m.

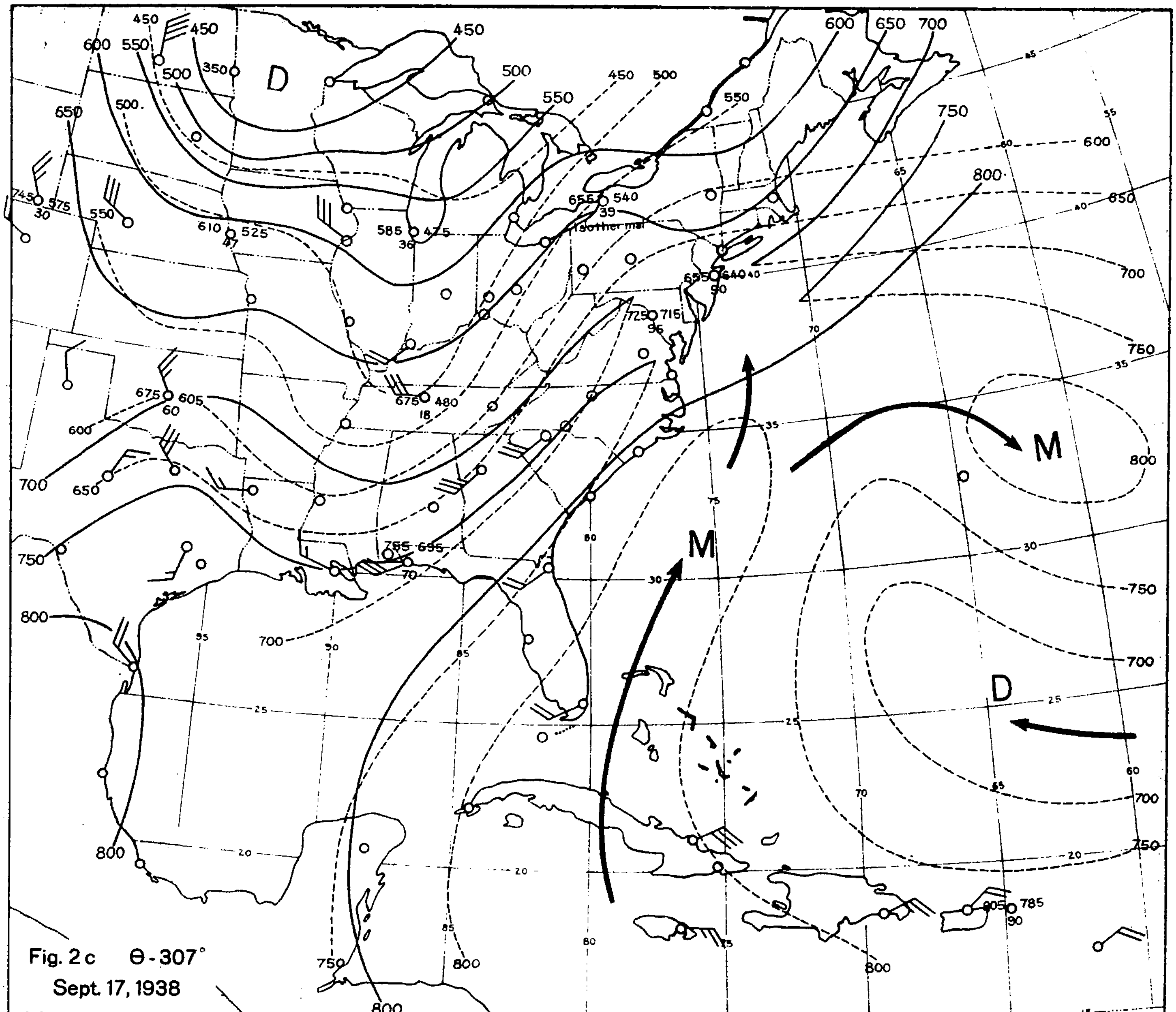


Fig. 2 c Θ-307°
Sept. 17, 1938

speed is 21°. Over land, the roughness parameter increases to about 70 to 100 centimeters, so that the angle at 25 meters per second is about 28°. These are for straight-line flow, but according to Haurwitz [5] this would be the same for curved flow at the earth's surface.

Thus the front would move westward as a warm front until it reached a position with reference to the isobars north of the LOW center where the front would cross the isobars at an angle of 21°, and at this point, therefore, the front would remain stationary. Slightly closer to, but still north of, the center, we see that the northward-moving storm would bring the front into a position where it would cross the isobars at less than 21° (point B, fig. 27). At this point the winds would be flowing across the isobars at an angle greater than that between the front and the isobars; therefore, the front at the ground will move eastward as a cold front.

It can be shown from figure 27 that in the case of a front oriented north and south, the farther west from the center the front is, the farther north of the east-west axis will the front start moving eastward as a cold front. The line AB represents the position south of which the winds would shift to slightly west of north, so that any north-south front would change from a warm to a cold front along the line AB. The angle that this line forms with the east-west axis is equal to the angle at which the air flows across the isobars. This is true because we have two right triangles ABC and BCD. The angles ABC and CDB are the right angles. The angle at C is the same for both triangles, and therefore angle CAB is equal to angle DBC.

Above it was stated that the southern end of this front would at first move westward as a warm front. As the line AB intersected the southern end of the front, it would become a cold front. As the southern end of the front approached the rear of the storm, the winds would become more and more normal to it and the front would move, therefore, more and more rapidly eastward.

STRUCTURE OF THE STORM NEAR WASHINGTON

During the evening of the 20th, the autographic records indicated that the cold front passed Cape Hatteras. At the same time the hurricane was ENE of Jacksonville. As the hurricane moved northward during the night, the front must have moved westward as a warm front, but, as indicated by the thermograph record, Hatteras was never again in the warm air.

At 7:30 a. m., on the 21st, the hurricane was 140 miles ENE. of Hatteras. At this time there was a very definite front to the north of the hurricane center, as indicated by the three ships east of Cape Henry. Two of them farthest to the east report ENE. winds with temperatures of 77° and 76°; the other ship, a short distance to the west, reports a north wind with a temperature of 67°.

Now about this time some very valuable upper-air information was secured from the radiosonde observation made by the United States Navy at Anacostia, D. C., and two pilot-balloon ascents made by the Weather Bureau at the Wasington Airport, Arlington, Va. At the time the regular pilot-balloon ascent was supposed to be made, there was inclement weather, but improved weather conditions made it possible to take a balloon run at 7:52 a. m.

This upper-air sounding (fig. 28) showed very rapidly increasing northerly winds up to 800 meters, and then a decrease just as rapidly up to 2,400 meters. Between 2,000 meters and 2,400 meters the winds shifted from NNW. to S. It appears incongruous that the wind at 2,400 meters should be from the south with the center of the hurricane 350 miles to the southeast of Washington. An explanation of this will be shown presently. Above 2,400 meters, the winds again increased rapidly to 3,200 meters, then less rapidly to a top velocity of 60 miles per hour from the SSW. at 4,400 meters. The radiosonde ascent (fig. 29) taken 2 hours earlier shows cool air at low levels and warm moist air aloft, with two distinct inversions: One at 1,600 meters, the other at 3,300 meters. The decreasing wind velocity comes at 1,600 meters and the strong south wind at 3,200 meters. The author's first impulse was to put the front at the second inversion where the wind shifts. Of course, this would assume that the hurricane at this level was completely wiped out and that the pressure gradient was in agreement with a strong south wind.

However, there were several objections to this. In the first place, by placing the front at 3,100 meters it would mean that the slope of the warm front would be 1/90, which is rather steep for a warm front surface. Also, the potential temperature of the warm front surface seems to be too high for the corresponding surface temperature of the warm sector. The potential temperature at the top of the lower inversion is close to the potential temperature of the warm-sector temperatures.

A greater objection, of course, is to eliminating the hurricane at 10,000 feet. The fact that the very low pressure must exist even at 10,000 feet is known by use of the hypsometric equation. If we assume that the central pressure is 28.00 inches, and that a psuedo-adiabatic lapse rate exists, the pressure at 10,000 feet would be 19.55 inches, which is 1.12 inches lower than the observed pressure at that height over Washington. H. Wexler carried the computations further and found that, in order to obtain a pressure at the center in keeping with the strong southerly winds at Washington (20.88 inches at 10,000 feet), the mean temperature of the air column from the ground to 10,000 feet would have to be 58° C. higher than that given by the assumption of pseudo-adiabatic equilibrium! The pressure of 20.88 inches corresponded to the isobar that was originally drawn across the center in our first attempts to account for the strong south wind at Washington. However, such a mean temperature in the column of air is impossible.

From this reasoning, and from the winds at Washington, the hurricane appears to be a separate cyclonic circulation *within* a stream of air from the south, as depicted by figure 30. Believing, then, that there is a separate cyclonic circulation, it is now possible to put the warm front at the lower inversion at Washington, which means, therefore, that the warm air must have swung cyclonically around the hurricane and come in from the north and north-northwest. The air from the north above the warm front is moving at a much less rate of speed than the cold air below. There is, then, the difference in velocity necessary to maintain a frontal slope with the cold air lying as a wedge west of the warm current.

Using the Washingon upper-air data, it is possible to draw a theoretical cross-section. This is shown in figure 31. On this cross-section, the winds are drawn with the orientation such that north is the top of the cross-section and east is to the right, and so on.

The first inversion is the front between the polar air and the tropical air. The second inversion would be the front between the tropical air of different trajectories. This storm is contrasted to the November 1935 hurricane which was in about the same position, but moving south and south-southwestward off the south Atlantic coast.

[5] Haurwitz, B. On the Change of Winds with Elevation under the Influence of Viscosity in Curved Air Currents, p. 262, *Gerlands Beiträge zur Geophysik*, Leipzig, 1935.

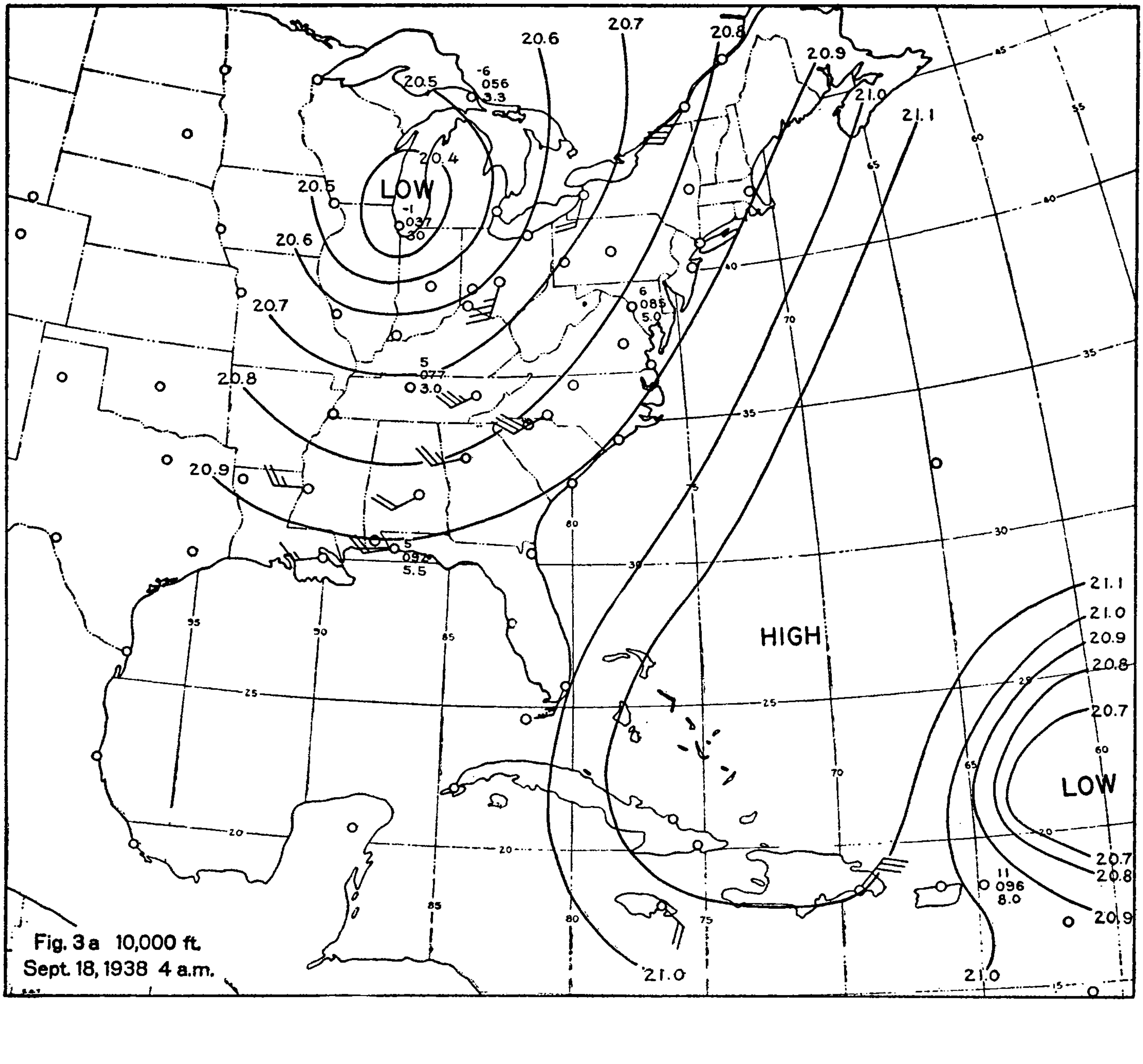


Fig. 3a 10,000 ft.
Sept. 18, 1938 4 a.m.

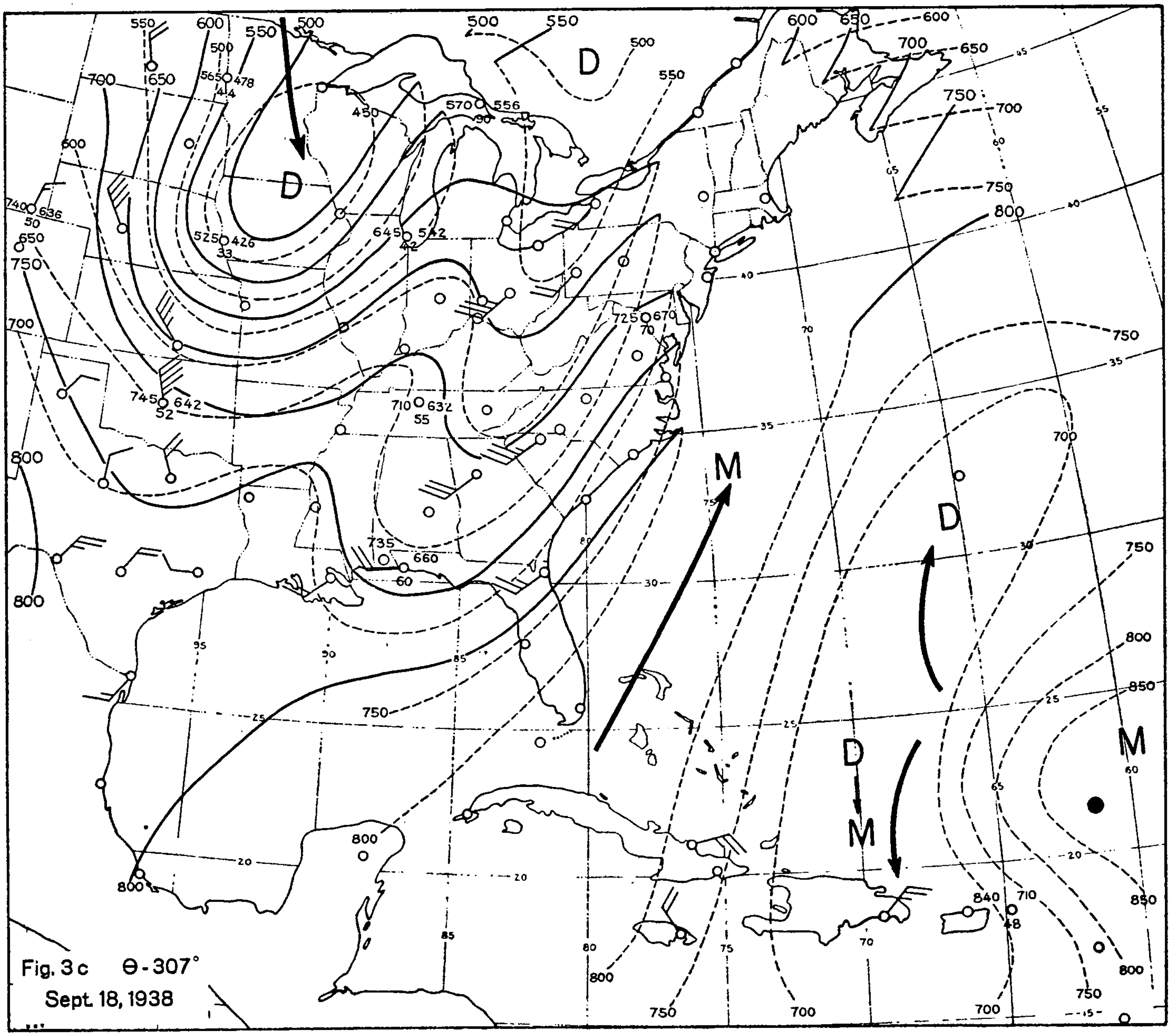


Fig. 3c Θ-307°
Sept. 18, 1938

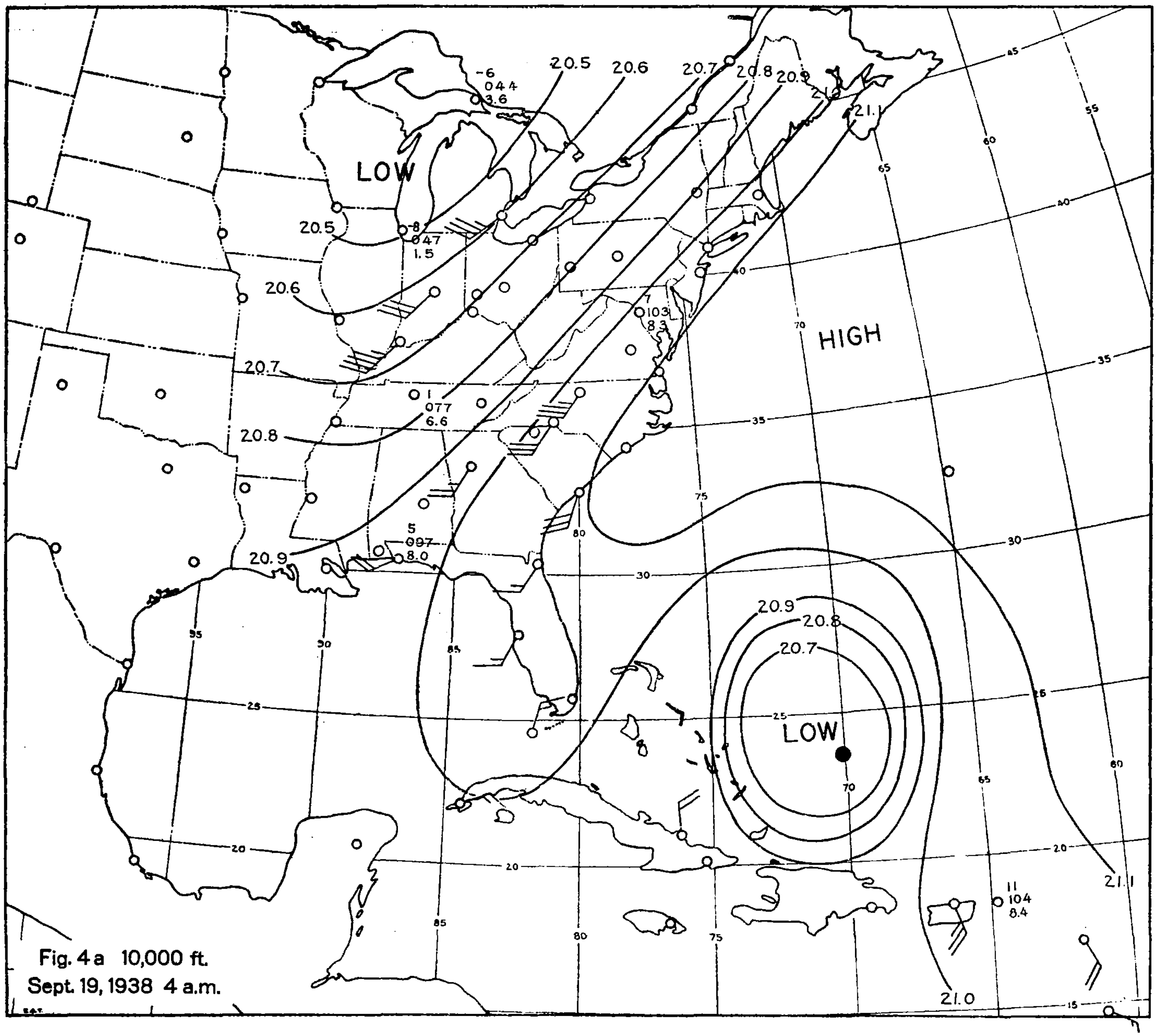


Fig. 4 a 10,000 ft.
Sept. 19, 1938 4 a.m.

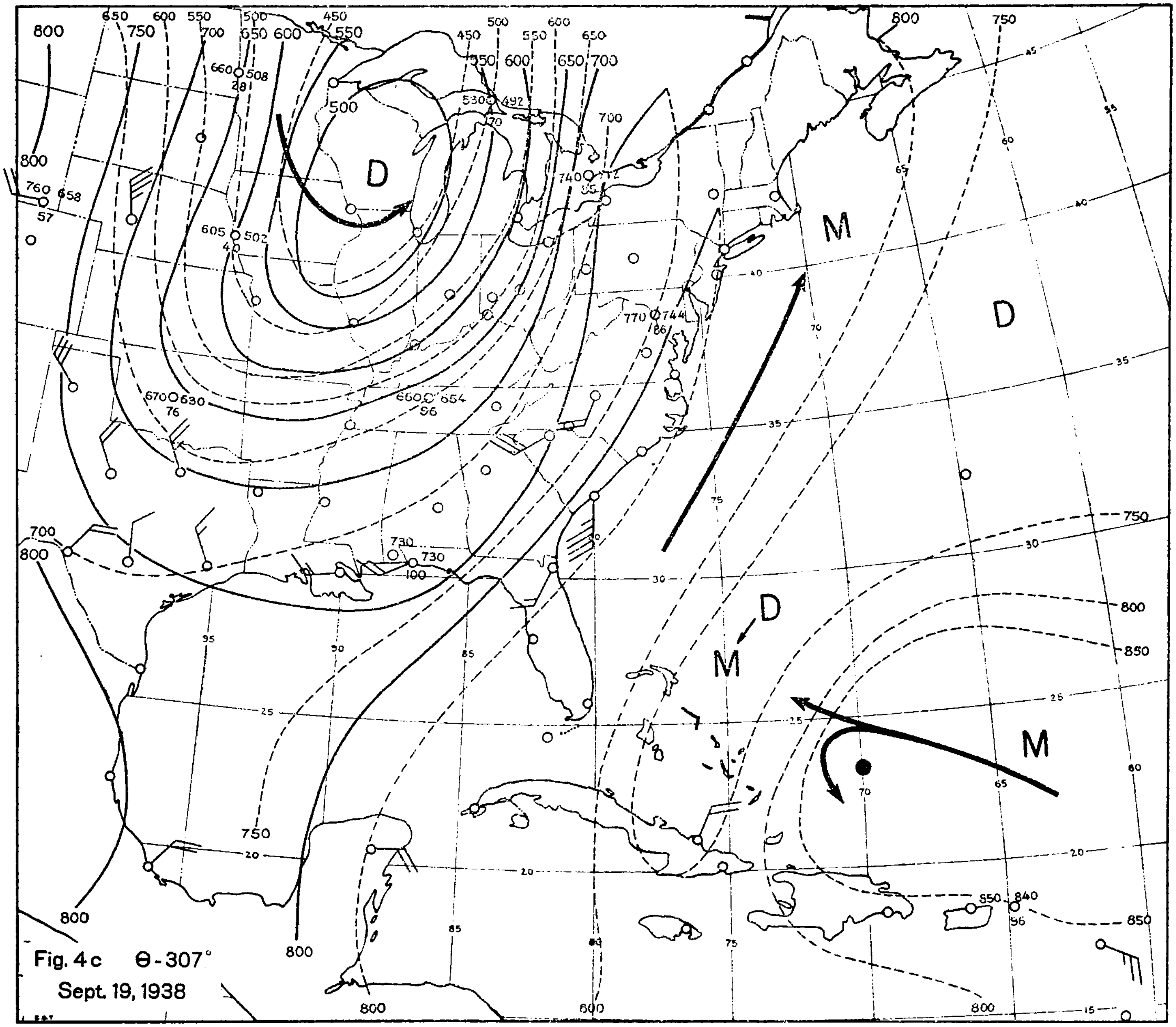


Fig. 4c Θ-307°
Sept. 19, 1938

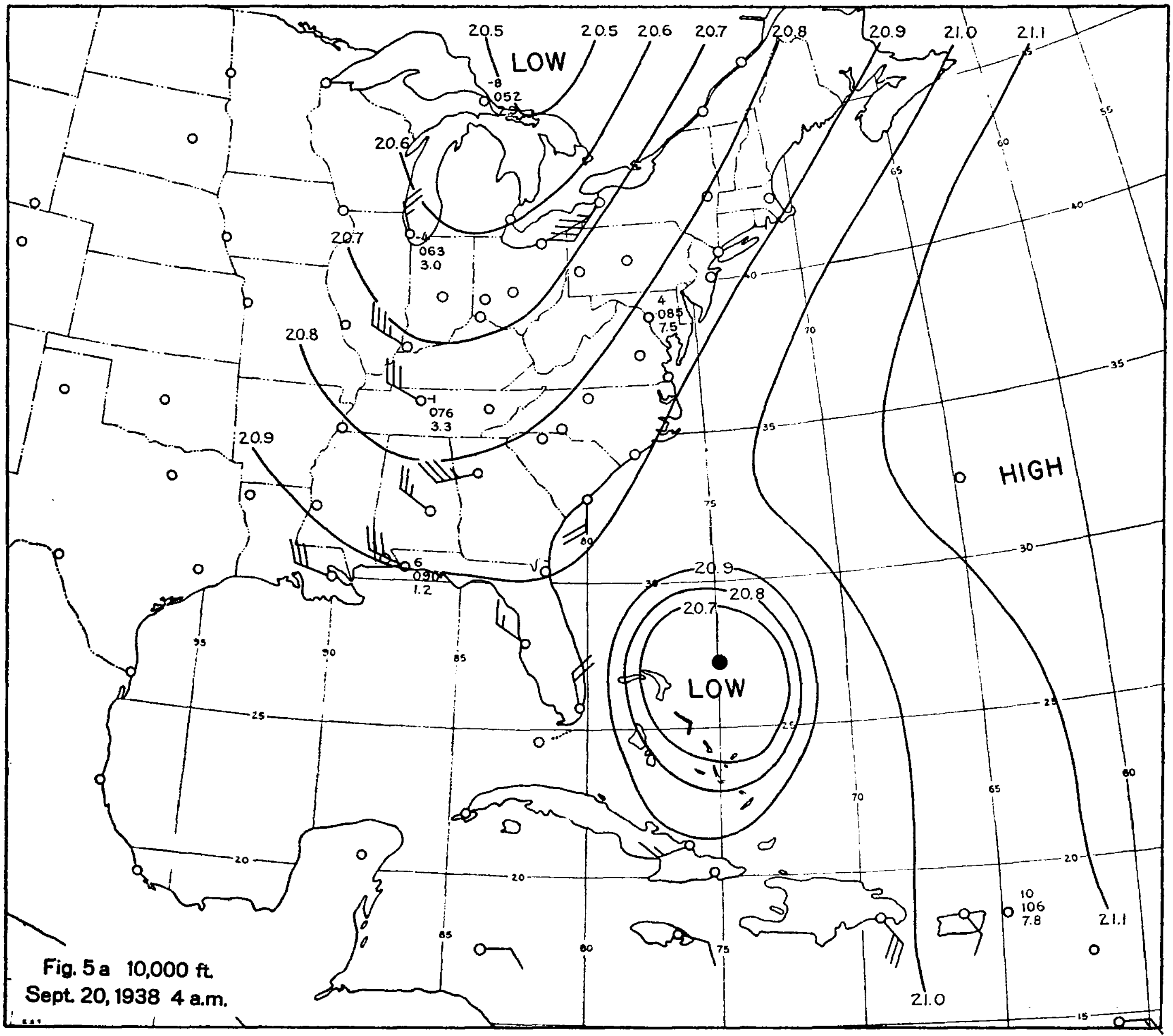

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Fig. 5 a 10,000 ft.
Sept. 20, 1938 4 a.m.

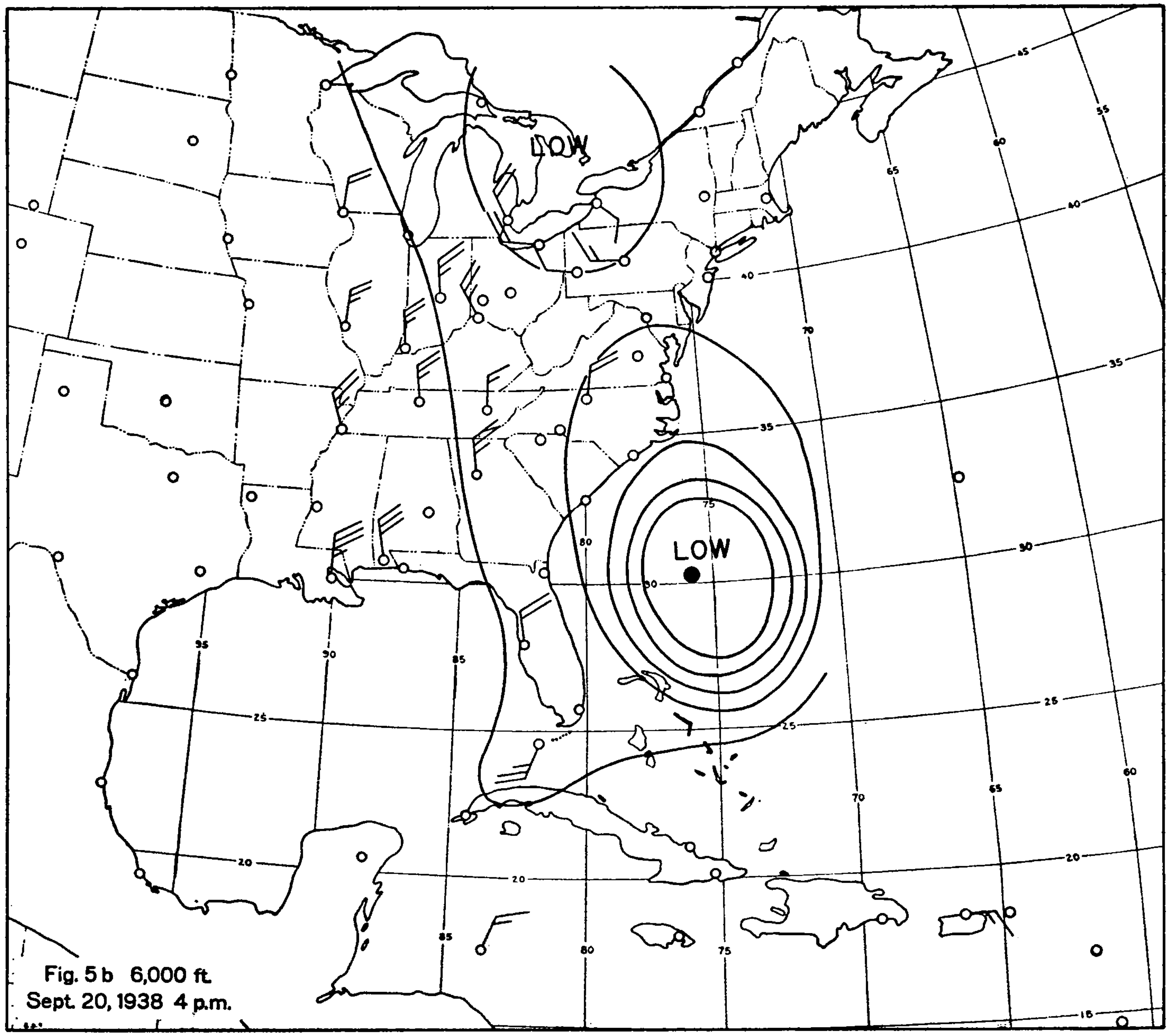


Fig. 5 b 6,000 ft.
Sept. 20, 1938 4 p.m.

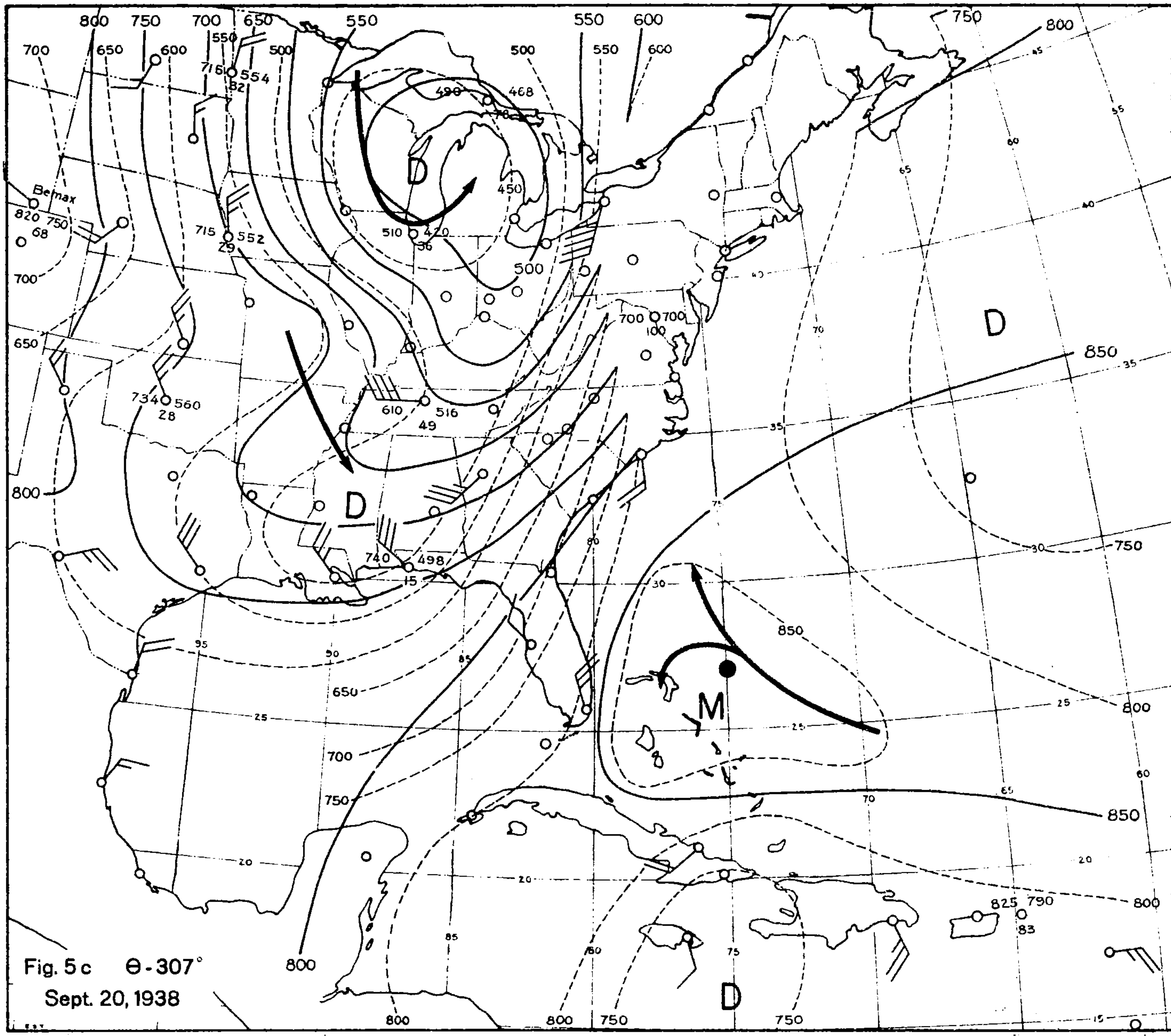


Fig. 5c θ-307°
Sept. 20, 1938

Byers [6] pointed out that the winds aloft over the eastern part of the country during this time were northerly.

HOURLY COURSE OF THE STORM

We return now to the surface analysis which will be carried through from 11 a. m. of the 21st to 12 a. m. of the 22d. These maps are constructed from data furnished by hourly airways teletype sequence reports and the autographic records of the regular Weather Bureau stations.

From 7:30 a. m. to 11 a. m. (figs. 12 and 13), the hurricane had shown rapid movement northward and at 11 a. m. was east of Norfolk, Va. The warm front had passed west of New Haven and Hartford. During the next 2 hours, the storm continued to accelerate in its movement so that by 1 p. m., according to figure 32, it was traveling at the rate of approximately 70 miles per hour, and was about 100 miles east-southeast of Atlantic City. Winds were already increasing along the southern New England coast.

Attention is drawn to the observation made at Mitchel Field at this hour. The wind is northeast, force 7 Beaufort, with a temperature of 70°. On figure 33, note how the temperature kept dropping slowly until 11 a. m., then rose sharply with the warm-front passage around noon. It is seldom that such distinct warm-front passages occur even in the winter. It is also interesting to note the discontinuity between Mitchel Field and Floyd Bennett Field, which is only 18 miles to the west. At Floyd Bennett the wind was north-northwest, force 7 Beaufort, and the temperature was 60° F.

At 2 p. m., the center was east of Lakehurst. There are no important changes, except that the wind reached hurricane force at Block Island.

The center reached the south shore of Long Island shortly before 3 p. m. The clear calm area experienced in the "eye" of a hurricane was reported from many points on Long Island. E. S. Clowes of Bridgehampton states that "clear, fairly calm interval occurred at Patchoque and at Port Jefferson." Brooks [7] reports that the calm center was experienced as far west as Brentwood and as far east as Mattituck. Thus, the diameter of the calm center is at least 43 miles, and if we are to believe there were 50 minutes of calm at Brentwood, then the "eye" must have been 50 miles wide, because the storm at that time was traveling at the rate of 60 miles per hour. The diameter of the "eye" seems to have become smaller as it moved into New England, because Hartford, which is west of the longitude of Mattituck, Long Island, did not experience the calm conditions. It is suggested by Brooks that the increased friction over land was responsible for the "dilation" of the central "eye."

Even though the east-west axis of the hurricane had not passed Mitchel Field by 3 p. m., the cold air had already moved in from the west. The wind at this time was north-northwest and the temperature had dropped to 59° F. This sudden temperature drop is very distinct on the thermograph record (fig. 33).

All the stations in approximately the same longitude and the same position, with respect to the storm, as Mitchel Field had similar traces on their thermograph records. Although Pittsfield, Mass., did not have a thermograph, the hourly sequences prove that the same front passages occurred there.

Miss Shirley Farr of Brandon, Vt., sent to the Weather Bureau her barograph and thermograph records, which were exceedingly helpful in the analysis of this storm. The thermograph trace (fig. 34) was very valuable in determining the front passages, and it will be noted that the trace shows the same pattern as was found at Mitchel Field.

Shortly after 3 p. m. the cold front east of the center passed Block Island. Unfortunately, the thermograph was upset by the high winds; however, the spotted record (fig. 35) shows the temperature dropped sharply near 3 p. m.

At 4 p. m. (fig. 18) the center had passed into southern Connecticut. The cold front east of the center was now north of the east-west axis, as is shown by the observations taken at Providence. The lowest pressure occurred there at the same time that it occurred at New Haven; also, there was a distinct temperature drop.

The central pressure at New Haven of 28.11 inches was higher than that reported at Hartford. Considering that the storm was moving practically straight north at the time and that New Haven experienced the calm eye that Hartford did not, it would seem that one of these pressures was in error. At New Haven, the barograph pressure had a higher correction value than any other station in the storm. A calibration of this instrument by the Instrument Division at the Central Office showed that the correction at the lowest pressure was in agreement with that made by the official in charge at the local office. Also, the barograph traces of the airport stations agreed respectively with their city offices.

Mr. Elliot, meteorologist for Eastern Airlines, called the author's attention to Brunt's reference [8] to Shaw's "cartwheel depression." In this discussion Shaw points out that the center of the winds with respect to the earth's surface is somewhat to the left of the lowest pressure in the path of movement. Because this storm cannot be treated as a "cartwheel" depression, it is impossible to tell exactly how far apart the center of the isobars, and the center of calm eye, would be. However, this gives a possible explanation as to why the two are not in agreement. The calm center at New Haven is very nicely depicted by a Burton's anemometer record of the Kopper's Coke Co. of that city (fig. 49).

The storm center had moved into southwestern Massachusetts by 5 p. m. (fig. 19). The front was swinging westward as a warm front through Vermont, Northfield, and Brandon showing very rapid rises in temperature (figs. 34 and 37). By 6 p. m. (fig. 20), the storm was centered over southern Vermont. Even though the center seemed to be filling rapidly now, it still maintained a distinct "eye." An interesting report was received from G. R. Putnam, of Dorset, Vt., who stated that, as the center passed, the wond velocity decreased very rapidly to practically calm. At the same time the clouds became broken. After the center passed northward, the wind did not increase appreciably because of the high range of mountains to the southwest. However, it did become overcast again.

The cold front in the eastern sector of the storm passed Concord, N. H., at about this time. The thermograph record (fig. 38) shows a very noticeable discontinuity. The temperature which was steady at 70° F. suddenly dropped to 64° F. at 6 p. m. The storm was now curving more to the northwest as indicated by its position at 7 p. m. (fig. 21). The sudden drop in temperature at

[6] Byers, H. R. The Meteorological History of the Hurricane of November 1935, Monthly Weather Review, vol. 63, No. 11, p. 322.

[7] Brooks, C. F., Hurricanes into New England, *The Geographical Review*, January 1939.

[8] Brunt, David. Physical and Dynamical Meteorology, 1934, p. 296.

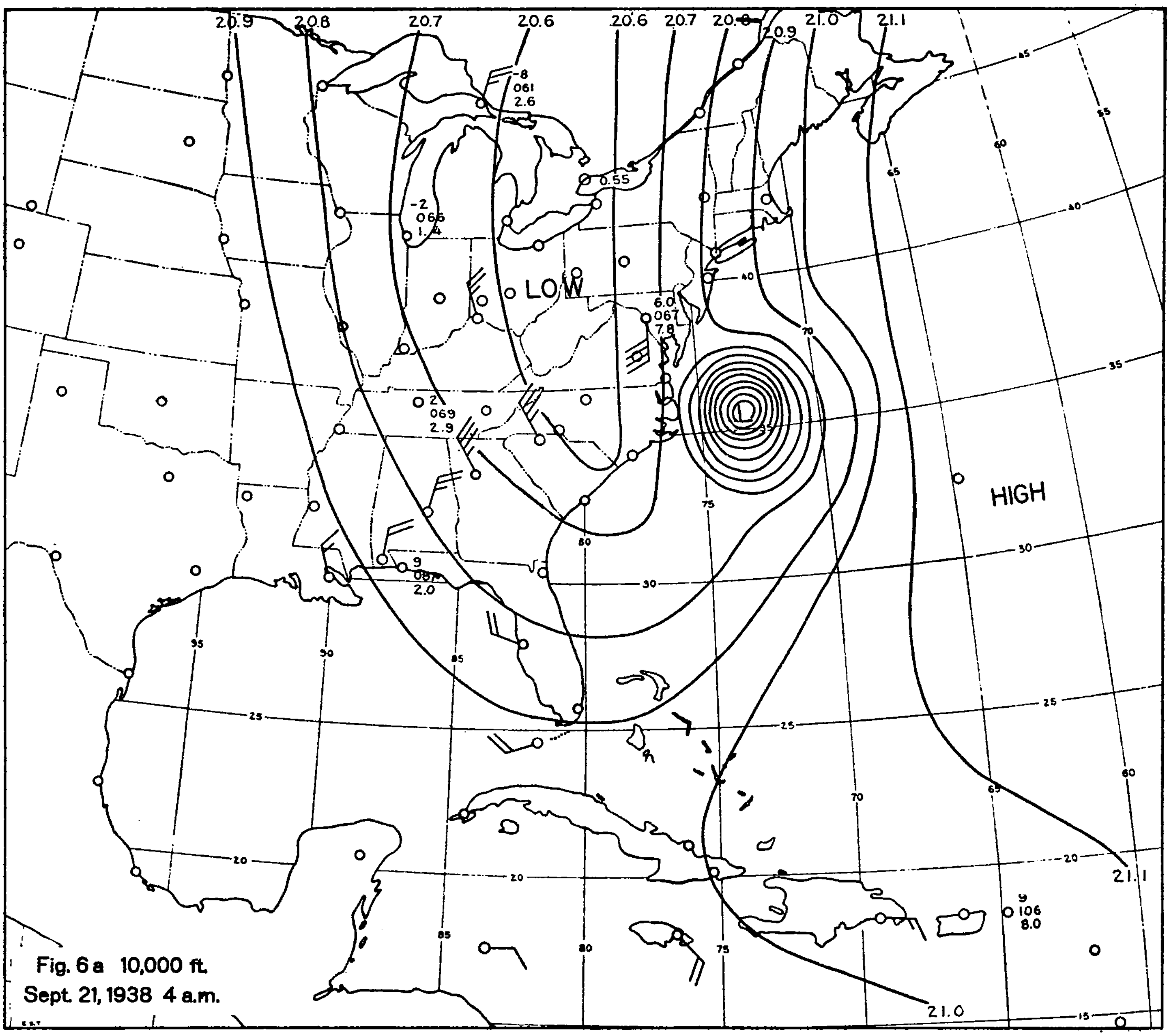


Fig. 6a 10,000 ft.
Sept. 21, 1938 4 a.m.

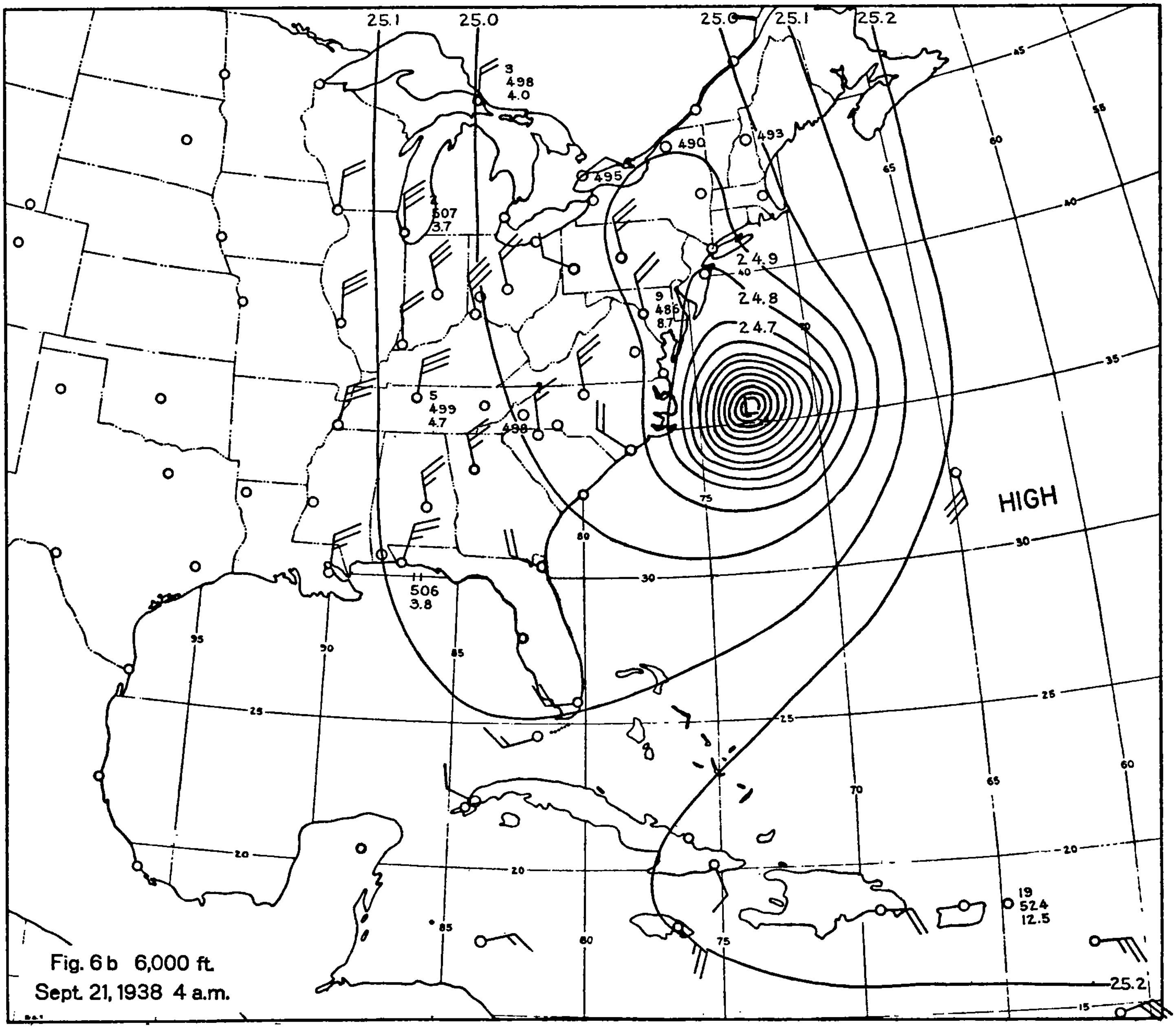


Fig. 6 b 6,000 ft.
Sept. 21, 1938 4 a.m.

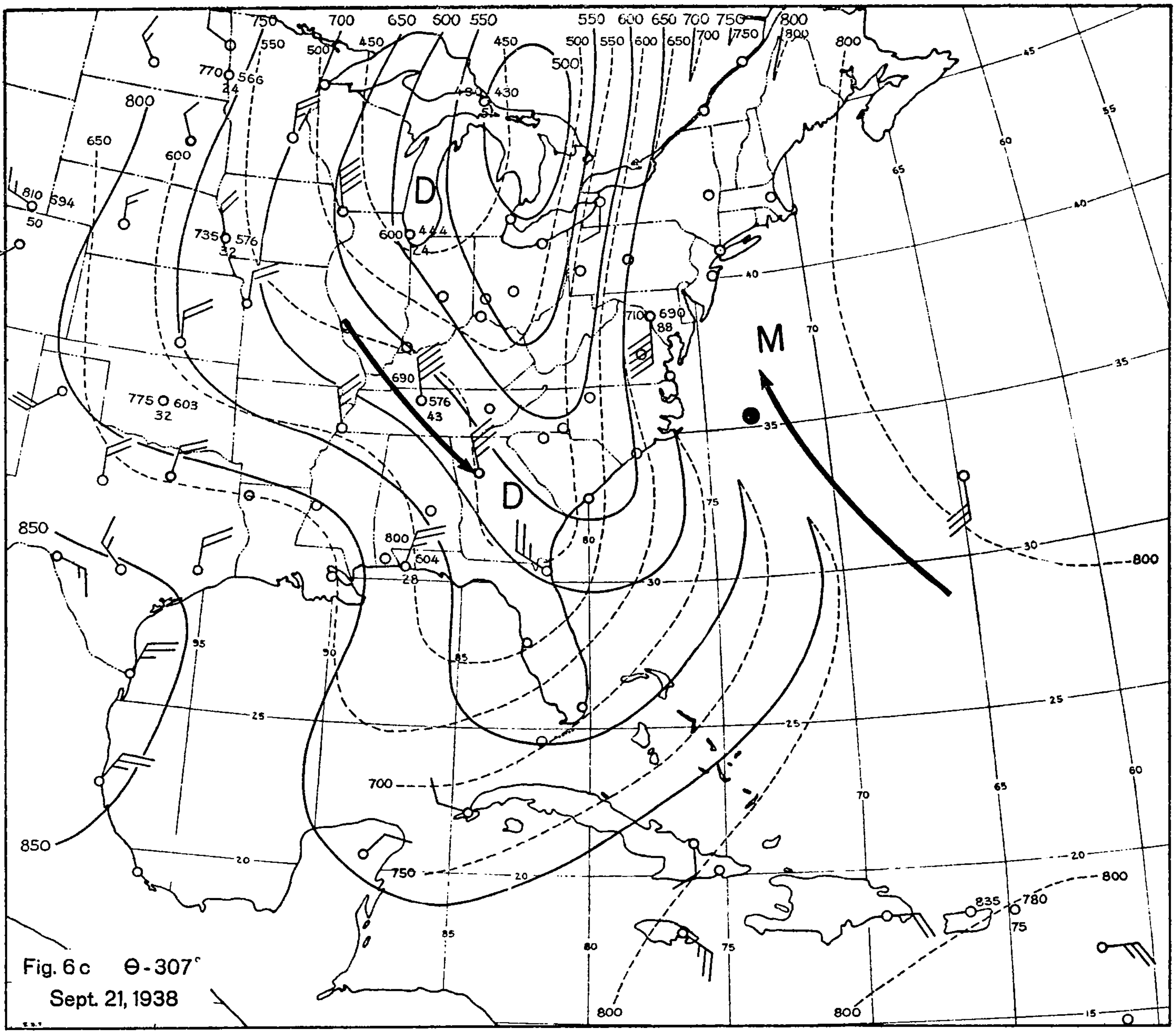


Fig. 6c Θ-307°
Sept. 21, 1938

Northfield was due to the cold front passing from the southeast.

Burlington experienced warm-sector weather for a short period of time with the warm-front passage shortly before 8 p. m. (fig. 39). As the center was now decelerating, the cold front in the eastern sector of the storm was overtaking the warm front to the west. Therefore, Burlington was passed shortly before 9 p. m. by the cold front from the southeast, and not as other stations in the same longitude, by the cold air coming in from the west. With the cold front from the southeast overtaking the warm front to the west, occlusion was bound to take place. At what definite time this occurred cannot be stated, but the synoptic chart of 9 p. m. (fig. 23) shows the occlusion taking place at the southern tip of the frontal system. The occlusion process was probably fairly rapid after this time because of the noticeable deceleration of the storm. At 10 p. m. (fig. 24) the whole northeast section of the country was now in the cold air. The cold front passed east of Eastport with a decided wind shift from southeast to southwest and a corresponding drop in temperature. The 7:30 a. m. map of September 22 showed this same cold front very distinctly just west of Halifax and Anticosti Island.

MAINTENANCE OF ENERGY

An important question at this point relates to why the storm maintained its energy so long after it passed inland. Those who are acquainted with hurricanes in the Gulf of Mexico realize that upon striking land, the hurricane usually dissipates very rapidly. This is due to: (1) The cutting off of the moisture which supplies energy in the form of latent heat of condensation, and (2) the increased friction over land. Of course, exactly the same things were operating in the New England hurricane, but there was another type of energy available which maintained this storm. After the hurricane acquired the deep polar air mass, there was further energy supplied by the potential energy of air-mass distribution. Therefore, after the storm reached the supply of cold air to the west, though the moisture content was reduced, the potential energy of mass distribution was still available to overcome some of the frictional influence. Another reason why the storm maintained its energy was that internal friction within the air was reduced. For a hurricane that moves into the Gulf States, the circulation aloft is usually light. In the case of the New England hurricane, however, the storm moved into a region having a strong cyclonic circulation aloft. Thus the internal friction within the air itself was greatly reduced. A rough schematic diagram (fig. 40) was drawn to depict the energy and friction forces and the changes that took place in them from the time of the storm's genesis until it passed into Canada. This diagram shows how the latent heat of condensation was the main source of energy at first and that the frictional effect was small. When the hurricane moved north of latitude 30° N., it acquired the fronts and polar air of this region. With the cold air on the western side, some of the latent heat of condensation was cut off. However, this was offset by energy of air-mass distribution.

When the center reached New England, the friction effect increased rapidly, which reduced the energy and caused the rapid filling.[9] However, the potential energy of air-mass distribution was still sufficient to overcome some of the friction effect, so that filling was not as rapid as usual.

[9] This is treated more fully by Raymond Wexler in a paper for his master's thesis, entitled, "The Filling of the New England Hurricane of September 1938."

EXPLANATION OF MINOR TROUGH

One of the most interesting and most puzzling phases of this storm was the distinct trough which passed across New Jersey, New York City, western Long Island, and southwestern Connecticut. Figures 41, 43, 44, 45, 46, 47, and 48 all show this dip in the barograph trace. Figure 41 is a barograph trace of Eastern Airlines at Newark, N. J., furnished to us by William Warren. Figure 42 shows a wind shift at Sandy Hook from west to northwest and back to southwest between 4 p. m. and 5 p. m. A meteorologist who did not have the opportunity to study this phenomenon minutely would have expected that this trough was indicative of a cold-front passage. If this were the case, this front and the trough would have to move from west to east with the path of air particles.

The time of the passage of this trough was plotted on the same chart as the time-distance graph of the storm center (fig. 32). It will be noted that the trough moved northward at the same rate of speed as the main center. This movement was approximately at right angles with the wind directions. Therefore, it could not have been a front at the surface.

Another possibility to explain the trough is the passage of a cold front aloft. However, this seems unlikely because the circulation aloft was adverse for such a frontal passage from the south. Also, if it were a cold front aloft, New Haven would not have experienced this trough effect.

A. F. Spilhaus has suggested that this trough might be explained by another cyclonic circulation within the main storm. This seems to be a reasonable explanation considering the movement corresponded to that of the center of the storm. This cyclonic eddy did not have a separate circulation, because it was too close to the main storm. However, it did cause a definite wind shift. A slight shift in wind from southwest to northwest occurred through New Jersey and Long Island. At New Haven, where there was not a wind shift, however, the wind did decrease in velocity as the low trough approached and increased after the trough passed. This is shown between the time of 6:30 to 7 p. m. (5:30 to 6 p. m. eastern standard time) on figure 23.

Thus, one of the most unusual and, from the viewpoint of the meteorologist, one of the most interesting storms passed into history, to be known as the New England hurricane of September 21, 1938. Actually, it was not a *tropical* hurricane in the strict sense of the word after it passed north of latitude 30° N., because in this area it was transformed into an extra-tropical storm, with a definite frontal structure and two distinct air masses—tropical maritime and polar continental. However, it was a cyclone which unfortunately maintained its hurricane intensity and, because of the peculiar temperature and wind distribution in the upper atmosphere, instead of following its normal course it moved straight northward over one of the most densely populated sections of the country.

The author wishes to take this opportunity to thank the following people who assisted in the development of this paper: The members of the Air Mass Section of the Weather Bureau, especially Clarence Gilbert, Pat Harney, George Mitchell, David Stevlingson, and Arthur Thomas for aiding in the construction of many of the charts; Wilson Reed at the Weather Bureau Office at Newark for furnishing many valuable data; William Warren of Eastern Air Lines, Miss Shirley Farr of Brandon, Vermont, and C. F. Brooks of Blue Hill Observatory, and the Koffer's Coke Company of New Haven, Conn., for giving us the use of their records; R. D. Elliott for his very helpful suggestions; and Harry Wexler and H. R. Byers for their many valuable suggestions and helpful comments.

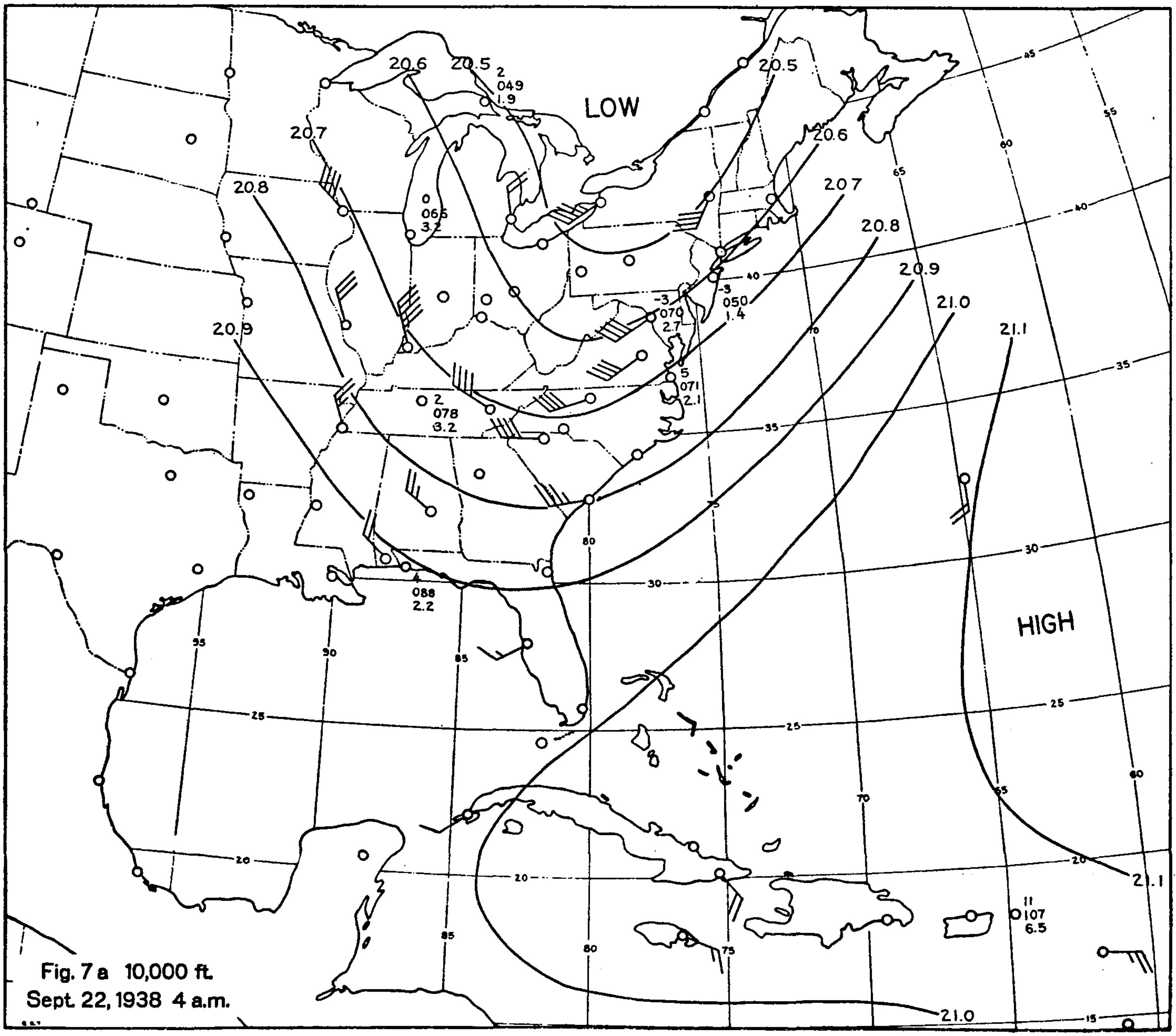


Fig. 7a 10,000 ft.
Sept. 22, 1938 4 a.m.

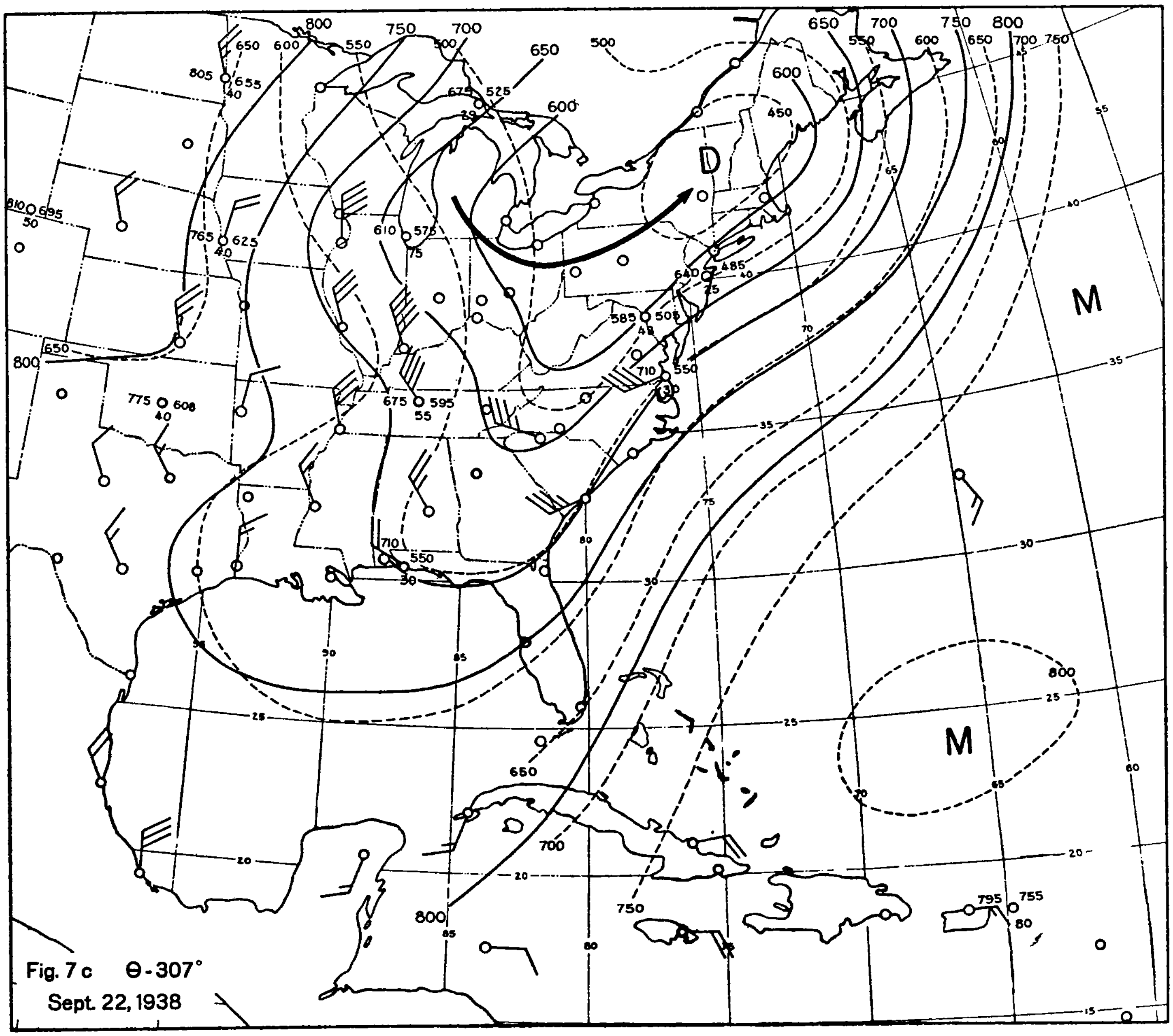
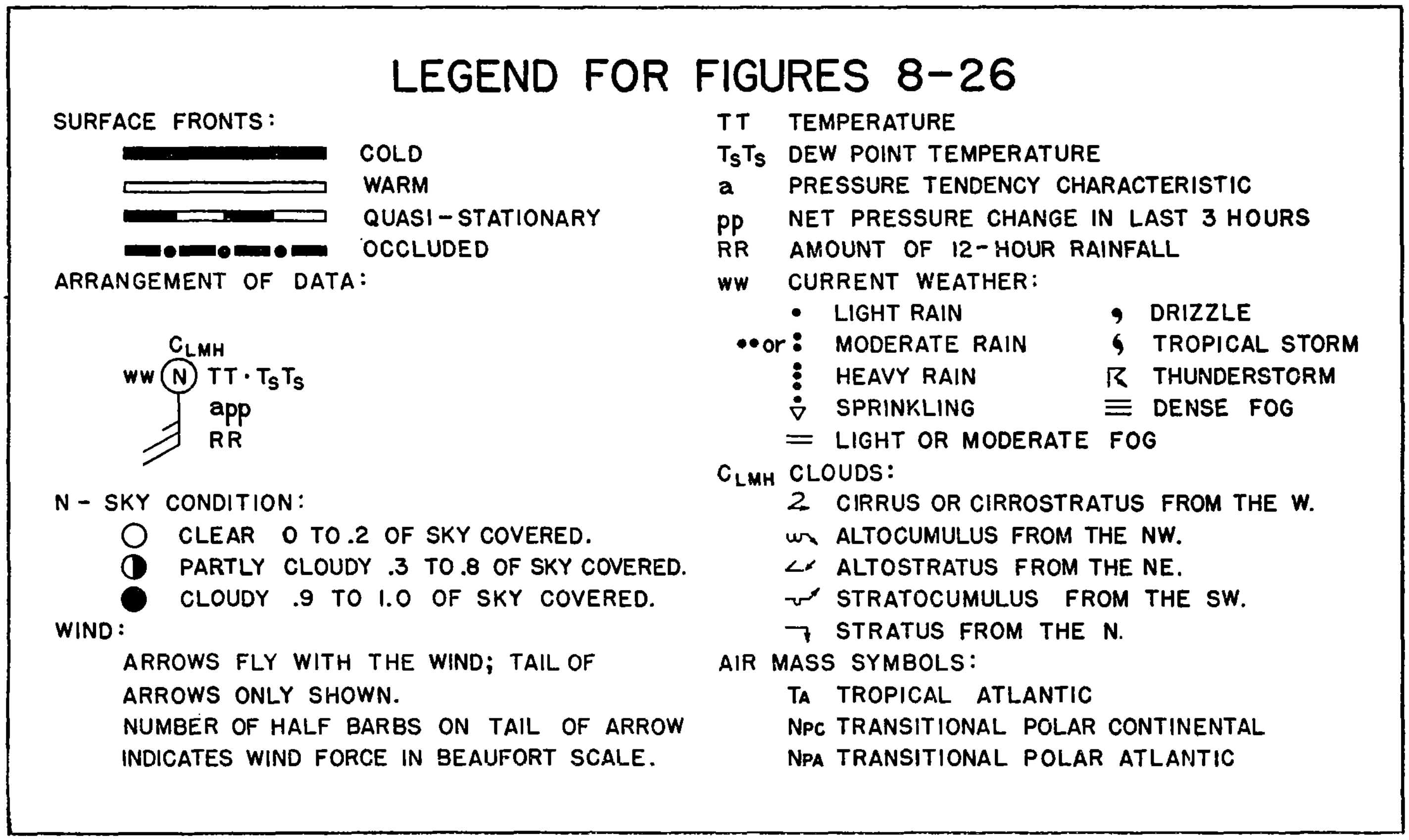


Fig. 7 c Θ-307°
Sept. 22, 1938


LEGEND FOR FIGURES 8-26
SURFACE FRONTS:
COLD
WARM
QUASI-STATIONARY
OCCLUDED
ARRANGEMENT OF DATA:
CLMH
ww N TT · TsTs
app
RR
N - SKY CONDITION:
CLEAR 0 TO .2 OF SKY COVERED.
PARTLY CLOUDY .3 TO .8 OF SKY COVERED.
CLOUDY .9 TO 1.0 OF SKY COVERED.
WIND:
ARROWS FLY WITH THE WIND; TAIL OF ARROWS ONLY SHOWN.
NUMBER OF HALF BARBS ON TAIL OF ARROW INDICATES WIND FORCE IN BEAUFORT SCALE.
TT TEMPERATURE
TsTs DEW POINT TEMPERATURE
a PRESSURE TENDENCY CHARACTERISTIC
pp NET PRESSURE CHANGE IN LAST 3 HOURS
RR AMOUNT OF 12-HOUR RAINFALL
ww CURRENT WEATHER:
LIGHT RAIN
or MODERATE RAIN
HEAVY RAIN
SPRINKLING
LIGHT OR MODERATE FOG
DRIZZLE
TROPICAL STORM
THUNDERSTORM
DENSE FOG
CLMH CLOUDS:
CIRRUS OR CIRROSTRATUS FROM THE W.
ALTOCUMULUS FROM THE NW.
ALTOSTRATUS FROM THE NE.
STRATOCUMULUS FROM THE SW.
STRATUS FROM THE N.
AIR MASS SYMBOLS:
TA TROPICAL ATLANTIC
NPC TRANSITIONAL POLAR CONTINENTAL
NPA TRANSITIONAL POLAR ATLANTIC

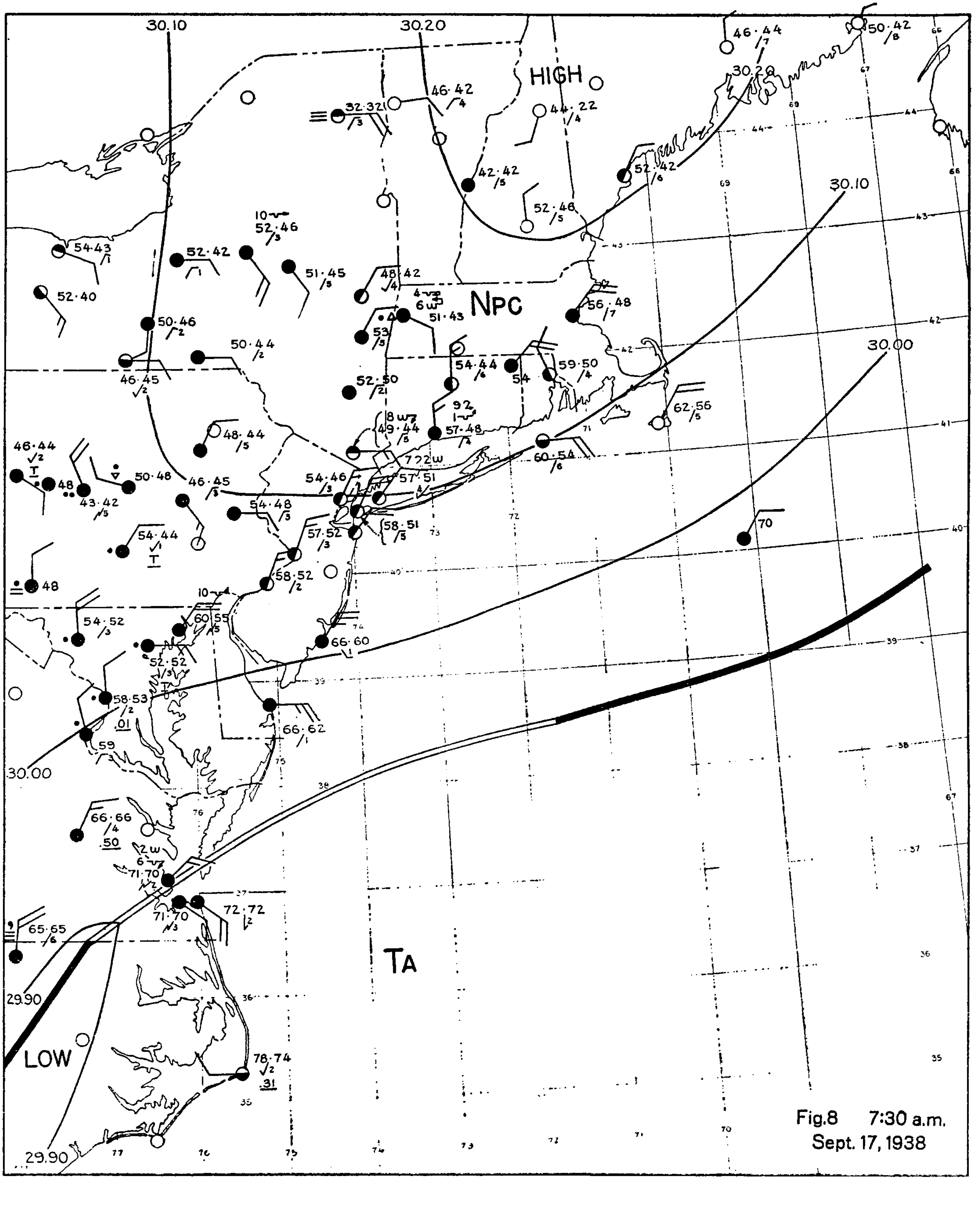


Fig. 8 7:30 a.m.
Sept. 17, 1938

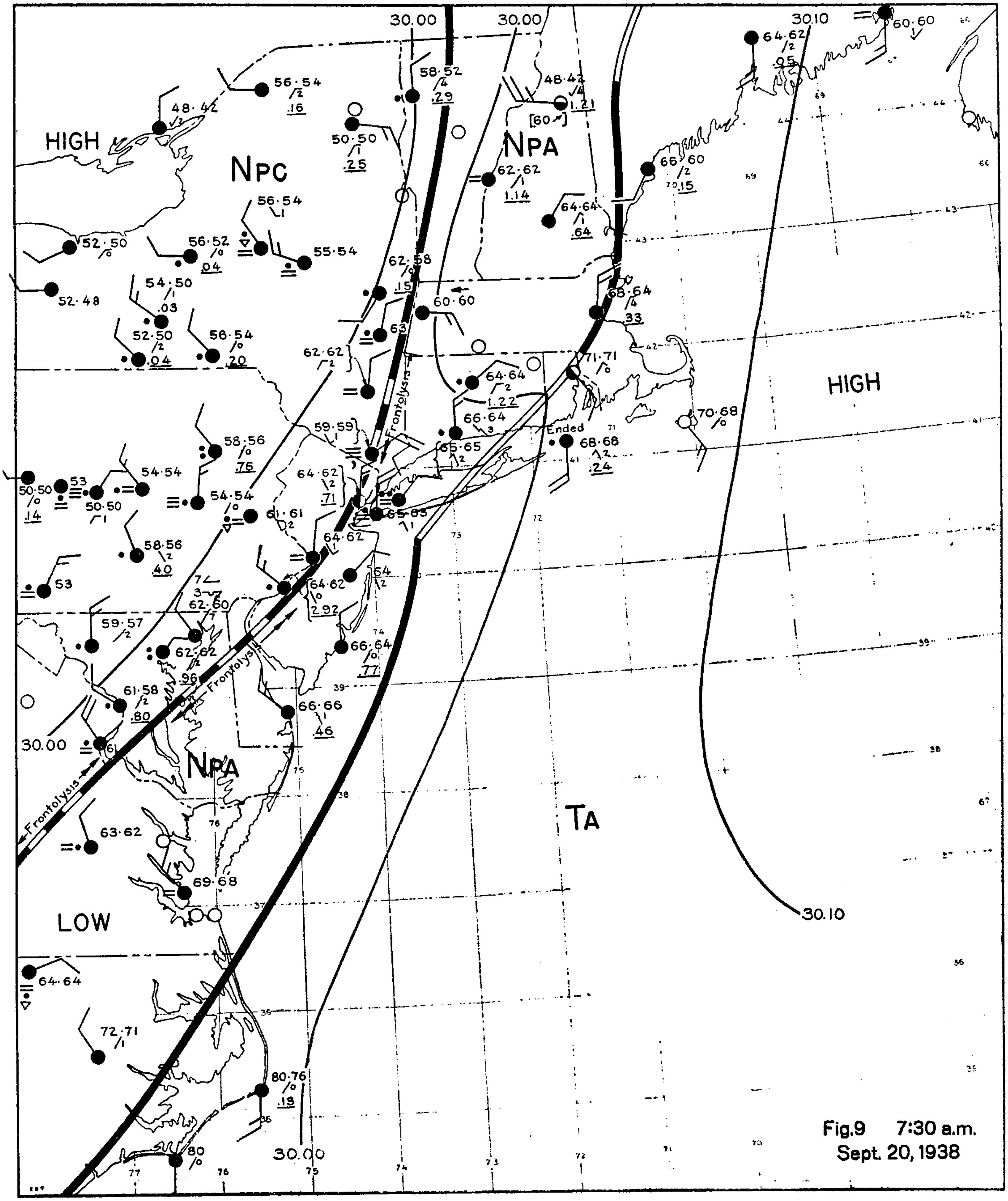
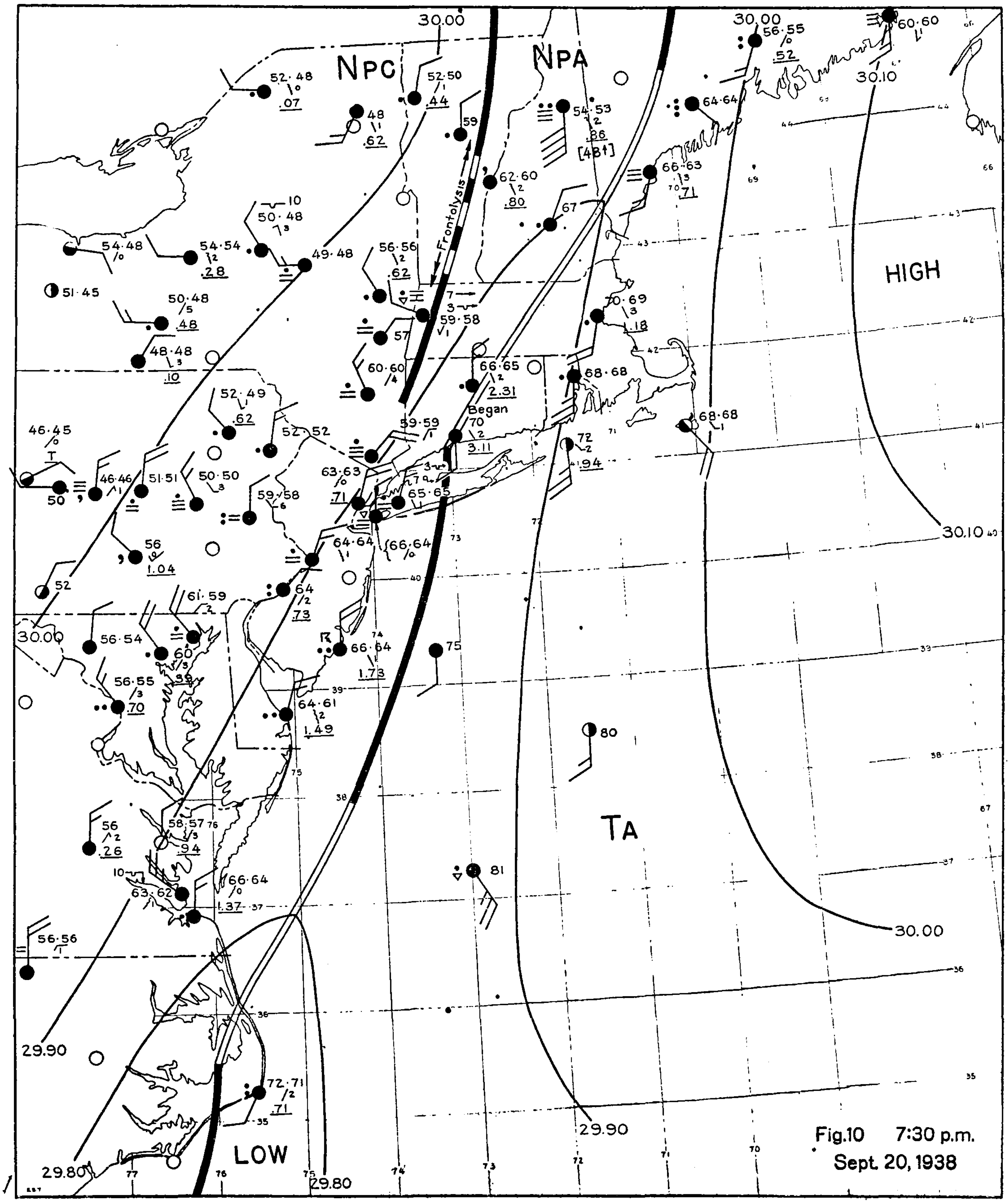


Fig.9 7:30 a.m.
Sept. 20, 1938


NPC
NPA
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TA
LOW
Frontolysis
Began
30.00
30.10
29.90
29.80
Fig.10 7:30 p.m.
Sept. 20, 1938

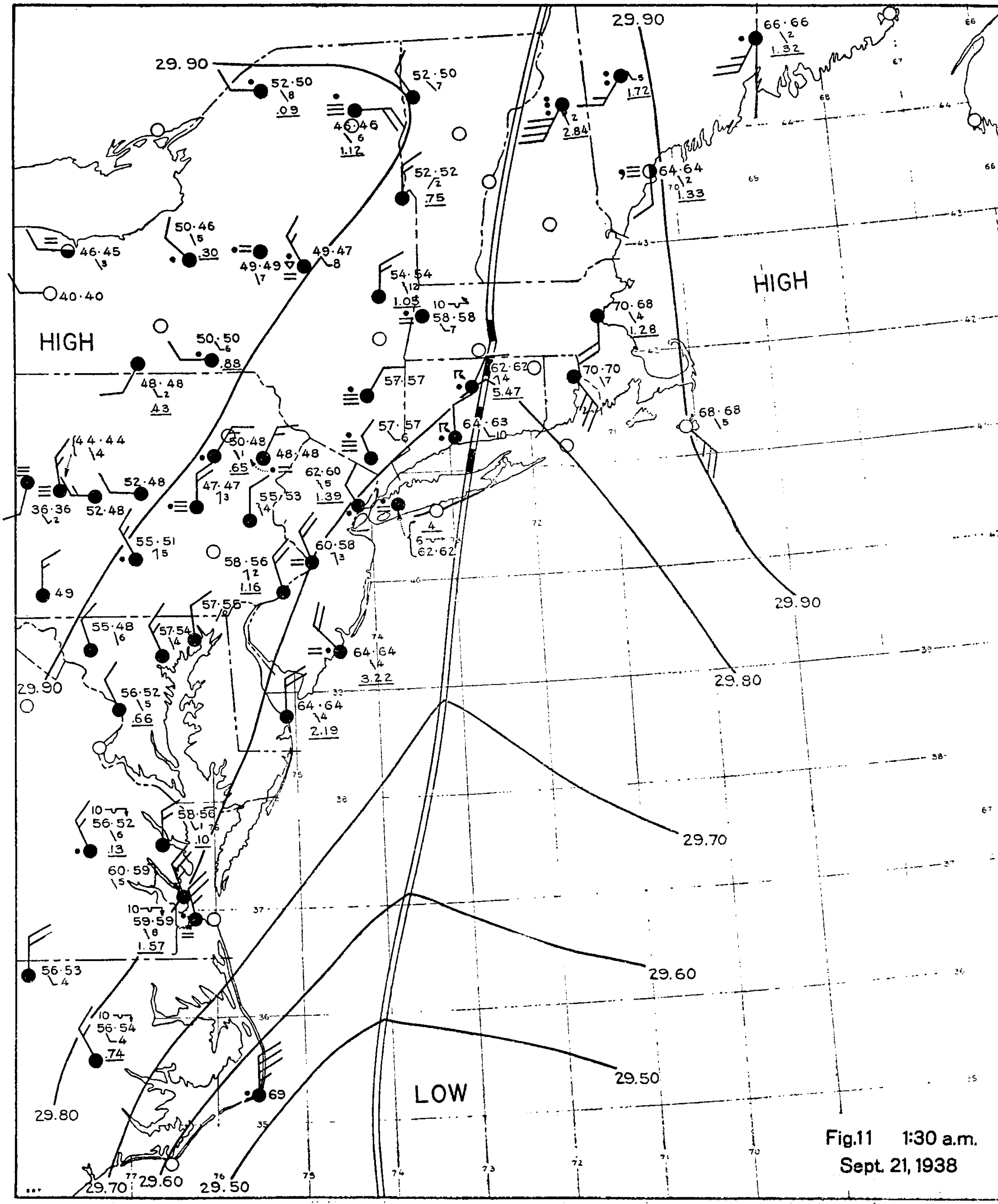


Fig.11 1:30 a.m.
Sept. 21, 1938

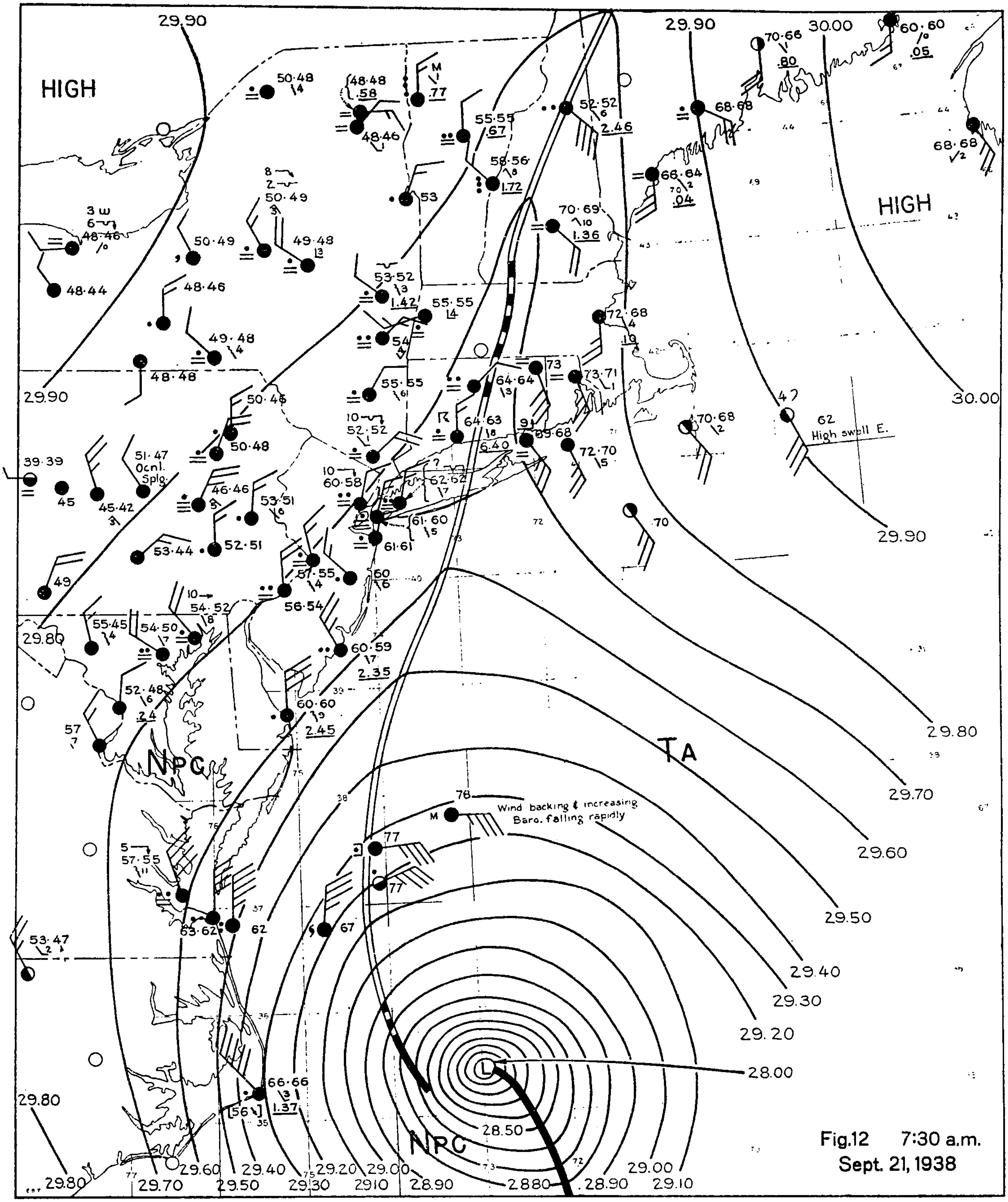


Fig.12 7:30 a.m.
Sept. 21, 1938

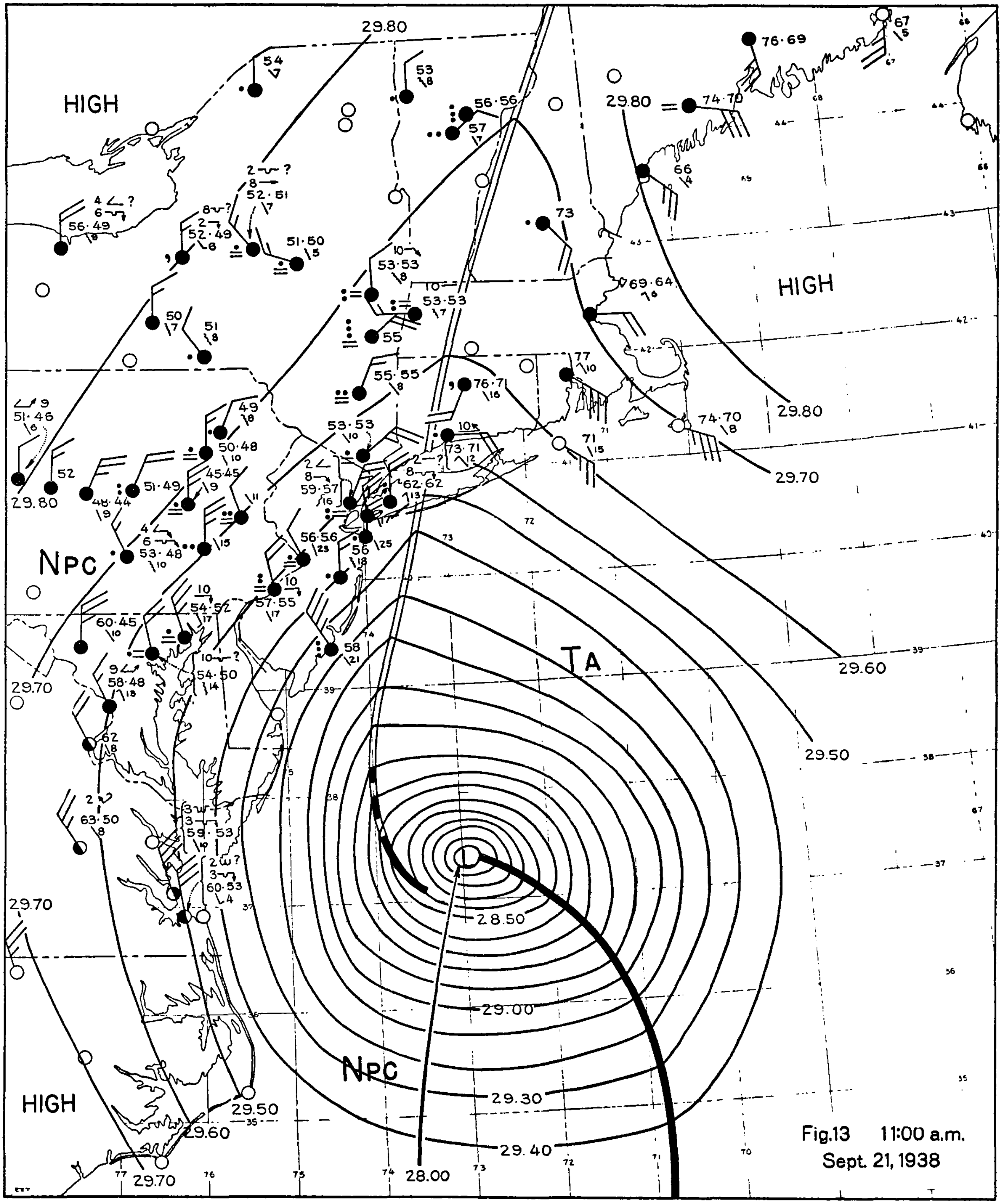


Fig.13 11:00 a.m.
Sept. 21, 1938

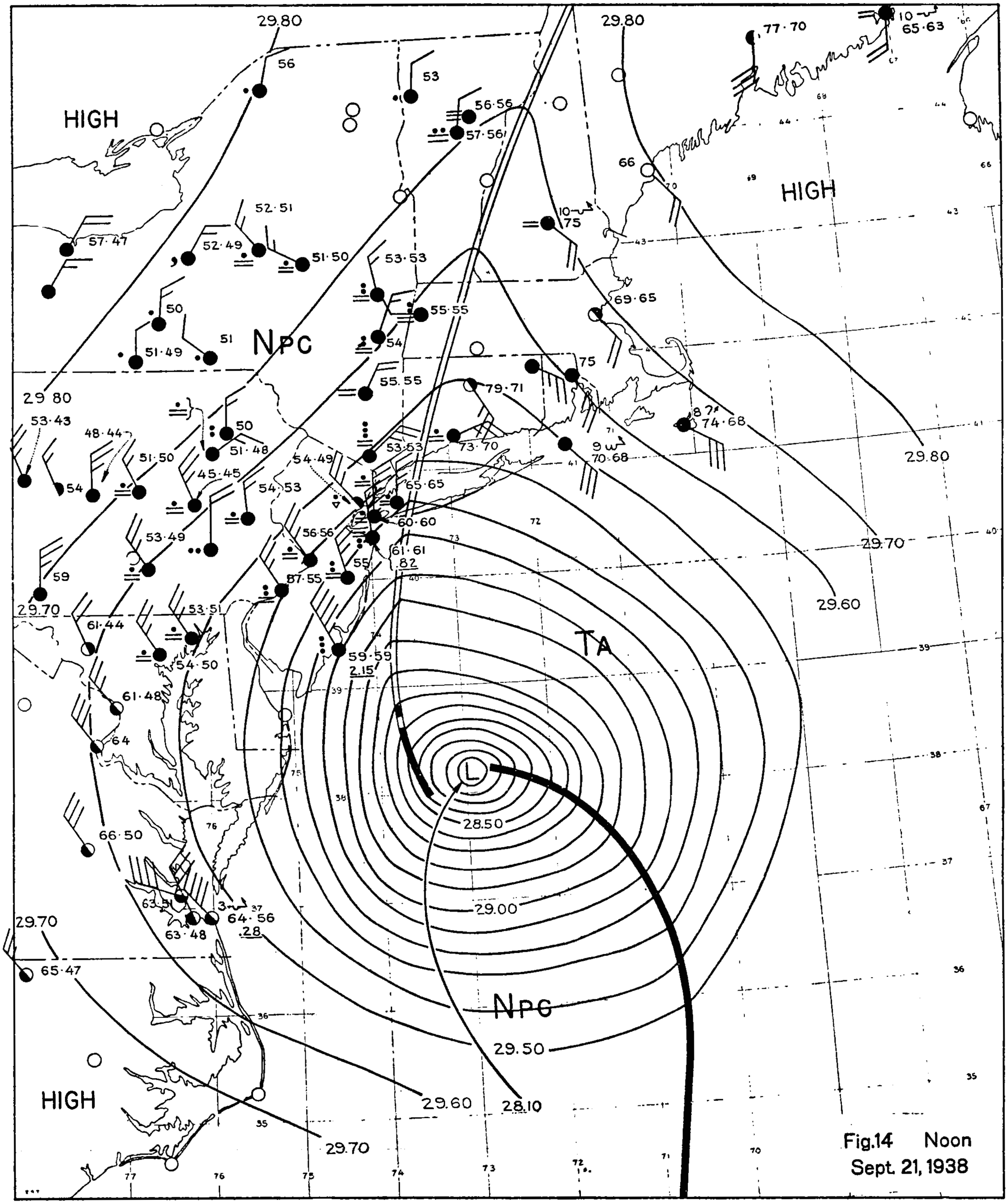


Fig.14 Noon
Sept. 21, 1938

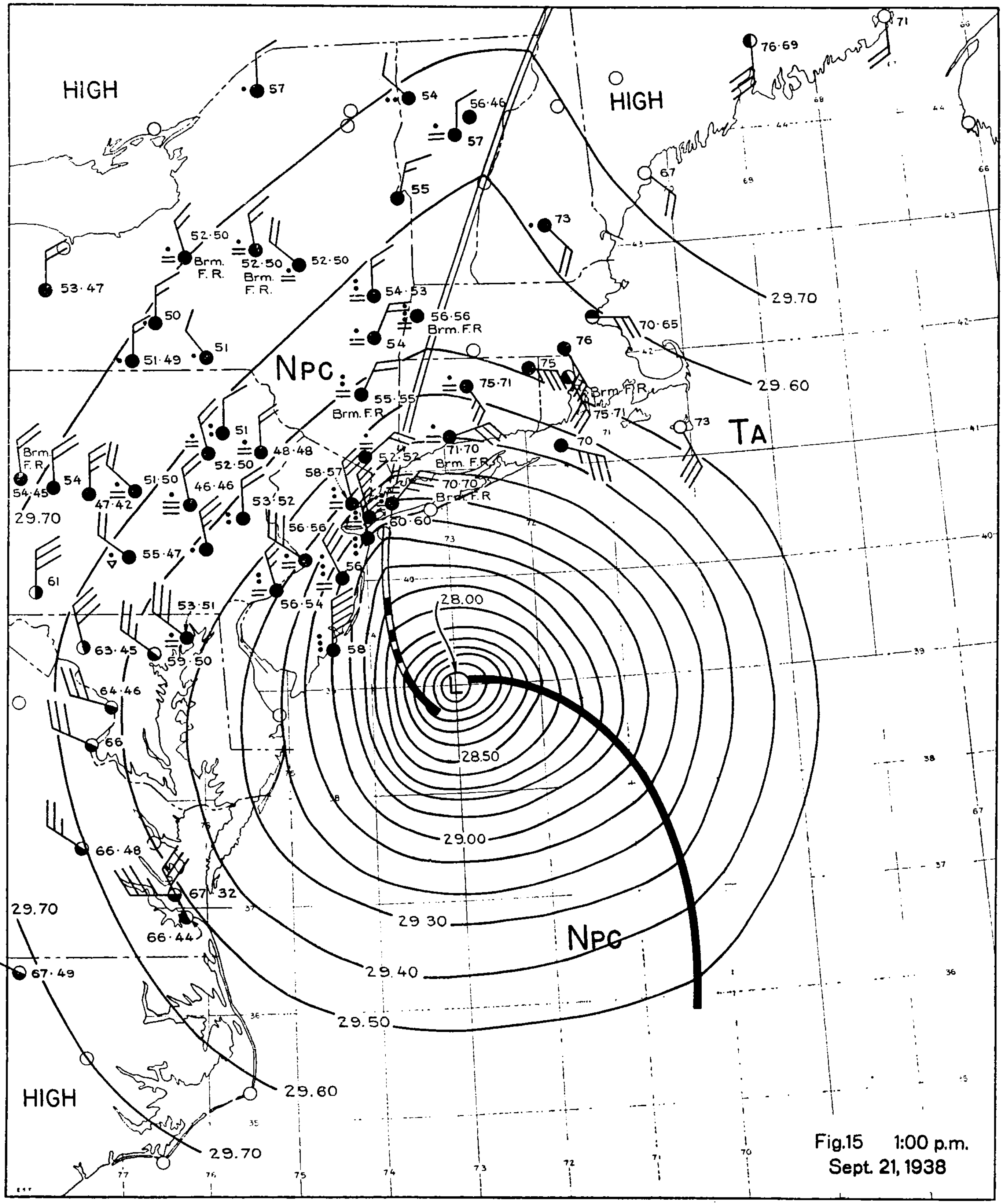


Fig.15 1:00 p.m.
Sept. 21, 1938

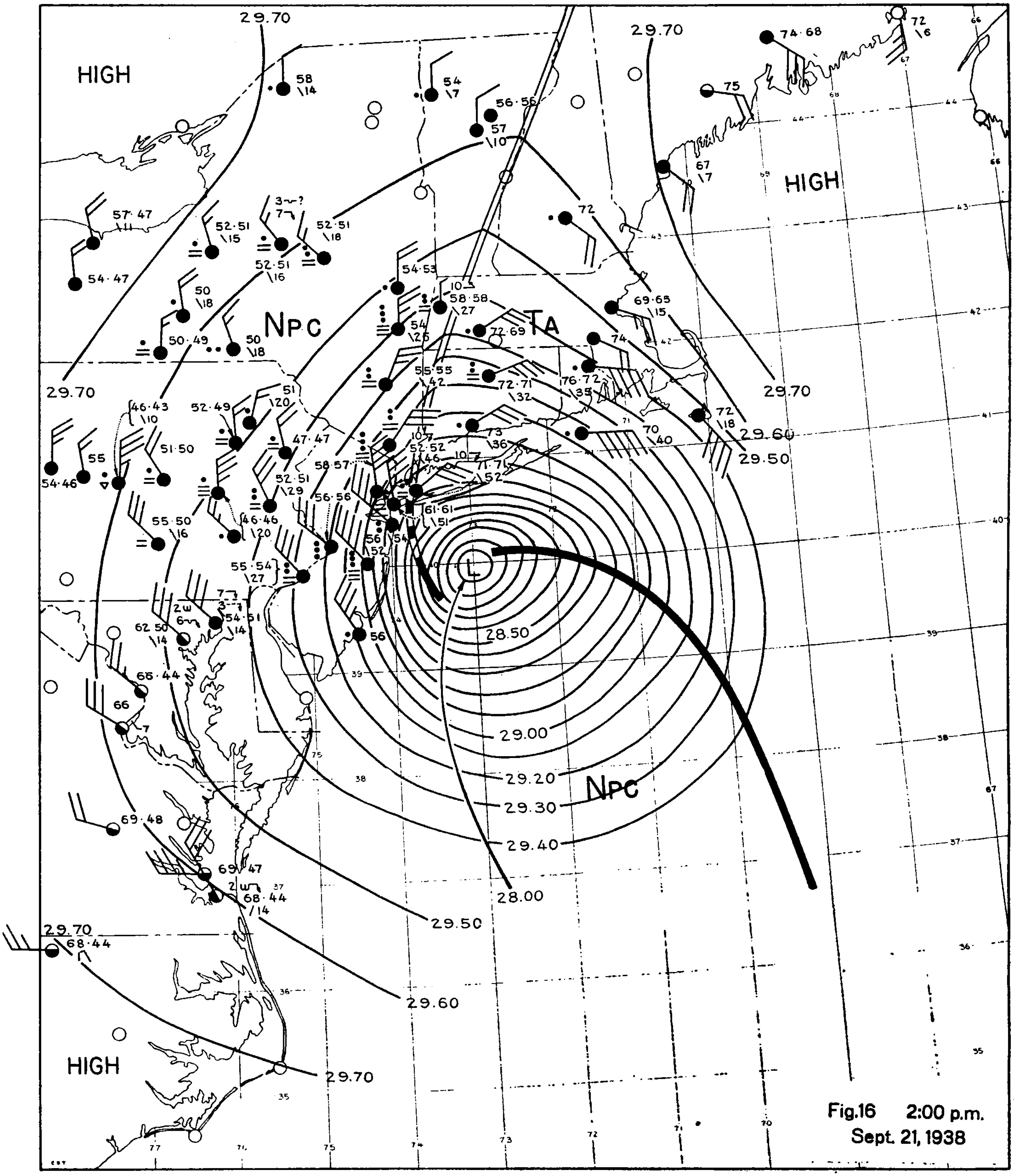


Fig.16 2:00 p.m. Sept. 21, 1938

182360—39——3

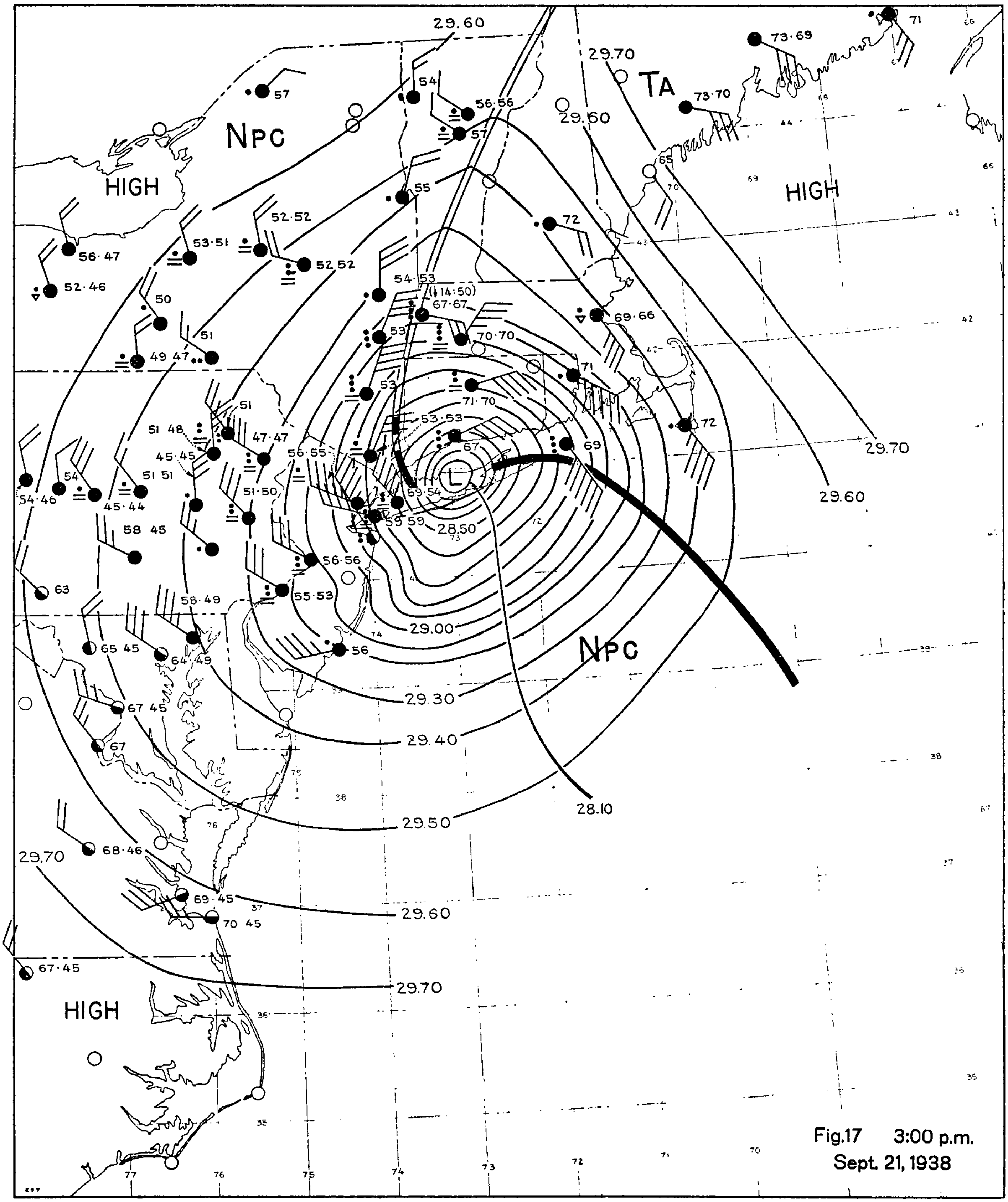
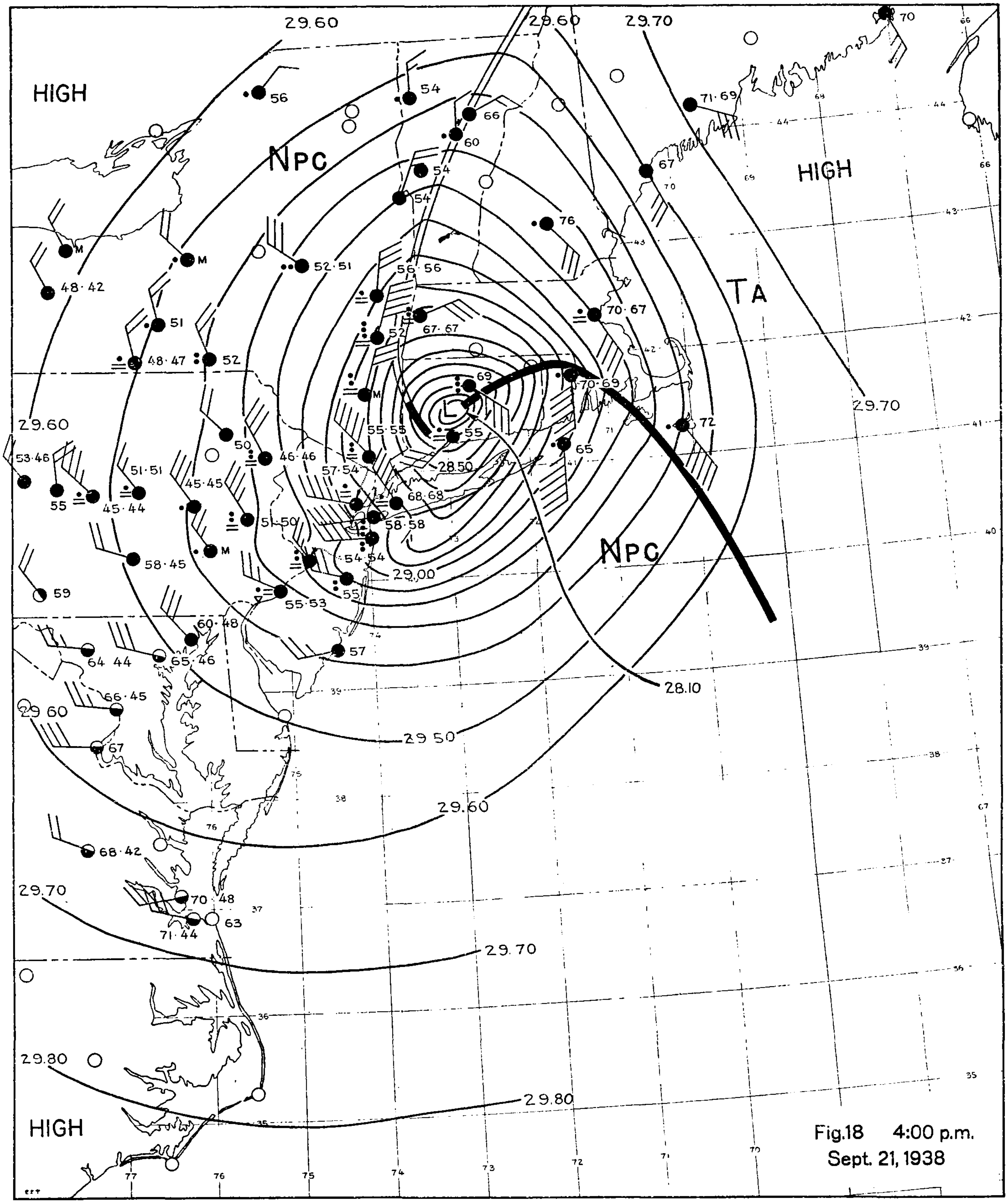


Fig.17 3:00 p.m.
Sept. 21, 1938


HIGH
NPC
HIGH
TA
NPC
HIGH
29.60
29.70
28.50
29.00
28.10
29.50
29.80
Fig.18 4:00 p.m.
Sept. 21, 1938

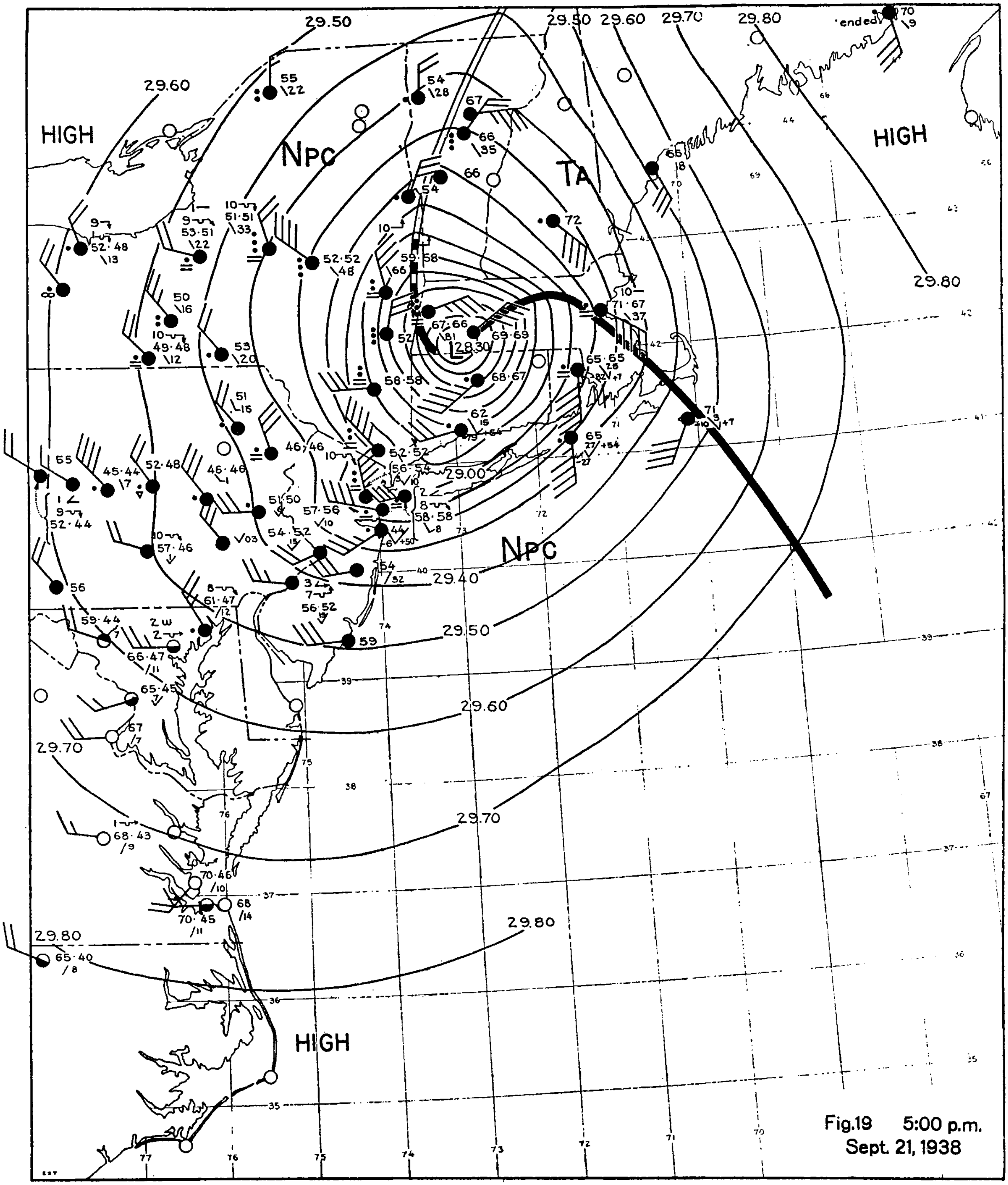


Fig.19 5:00 p.m.
Sept. 21, 1938

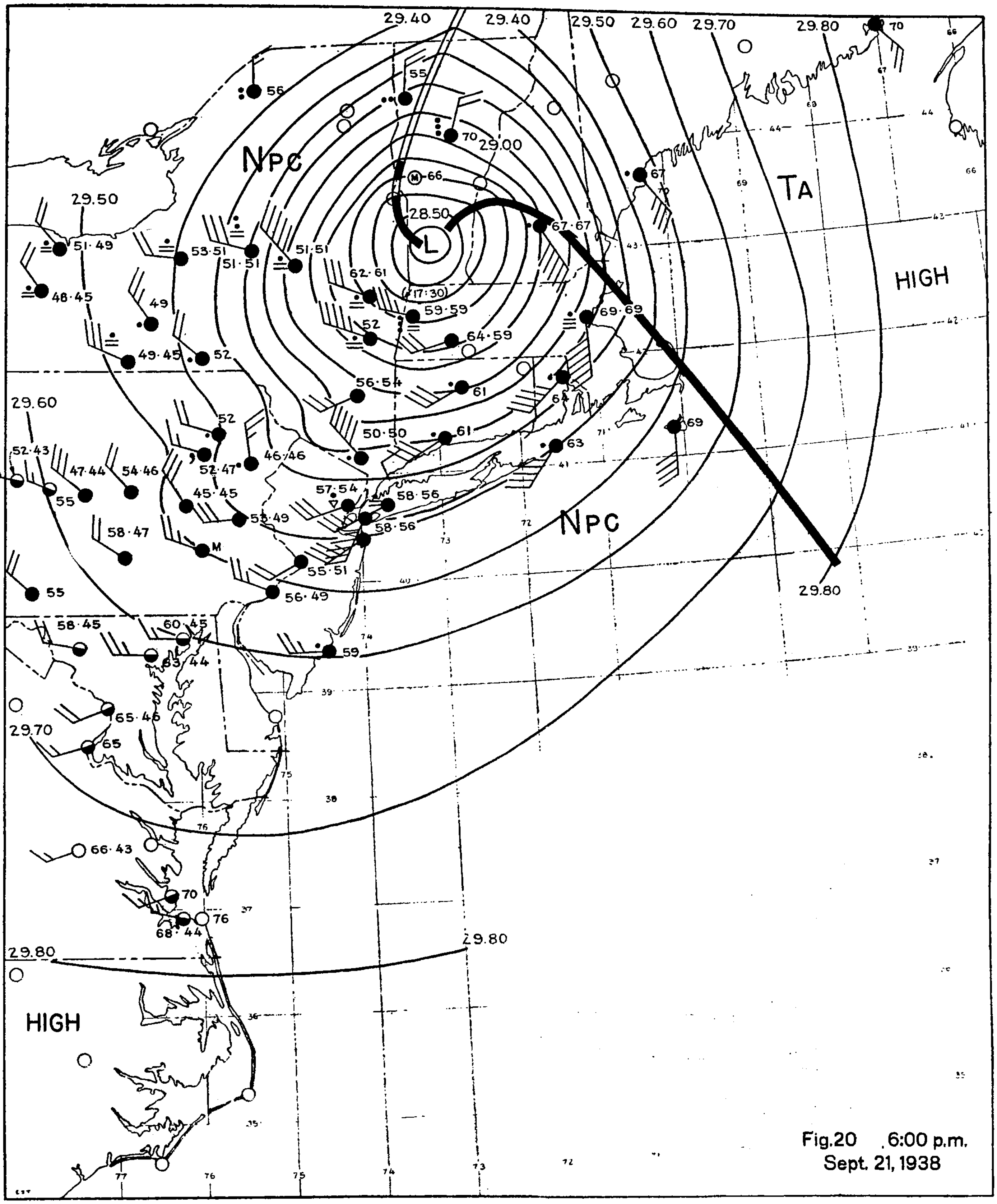


Fig. 20 , 6:00 p.m. Sept. 21, 1938

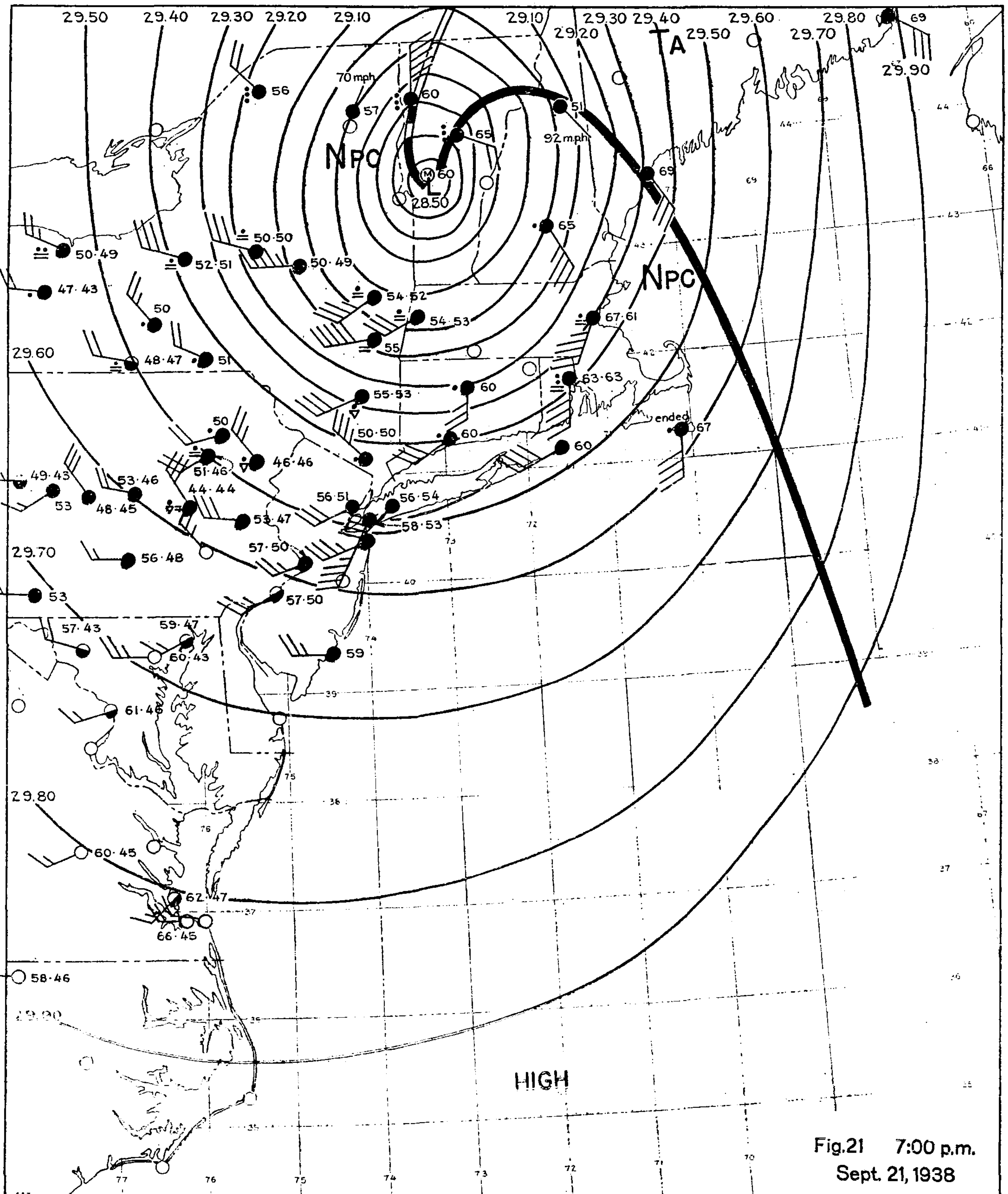


Fig.21 7:00 p.m.
Sept. 21, 1938

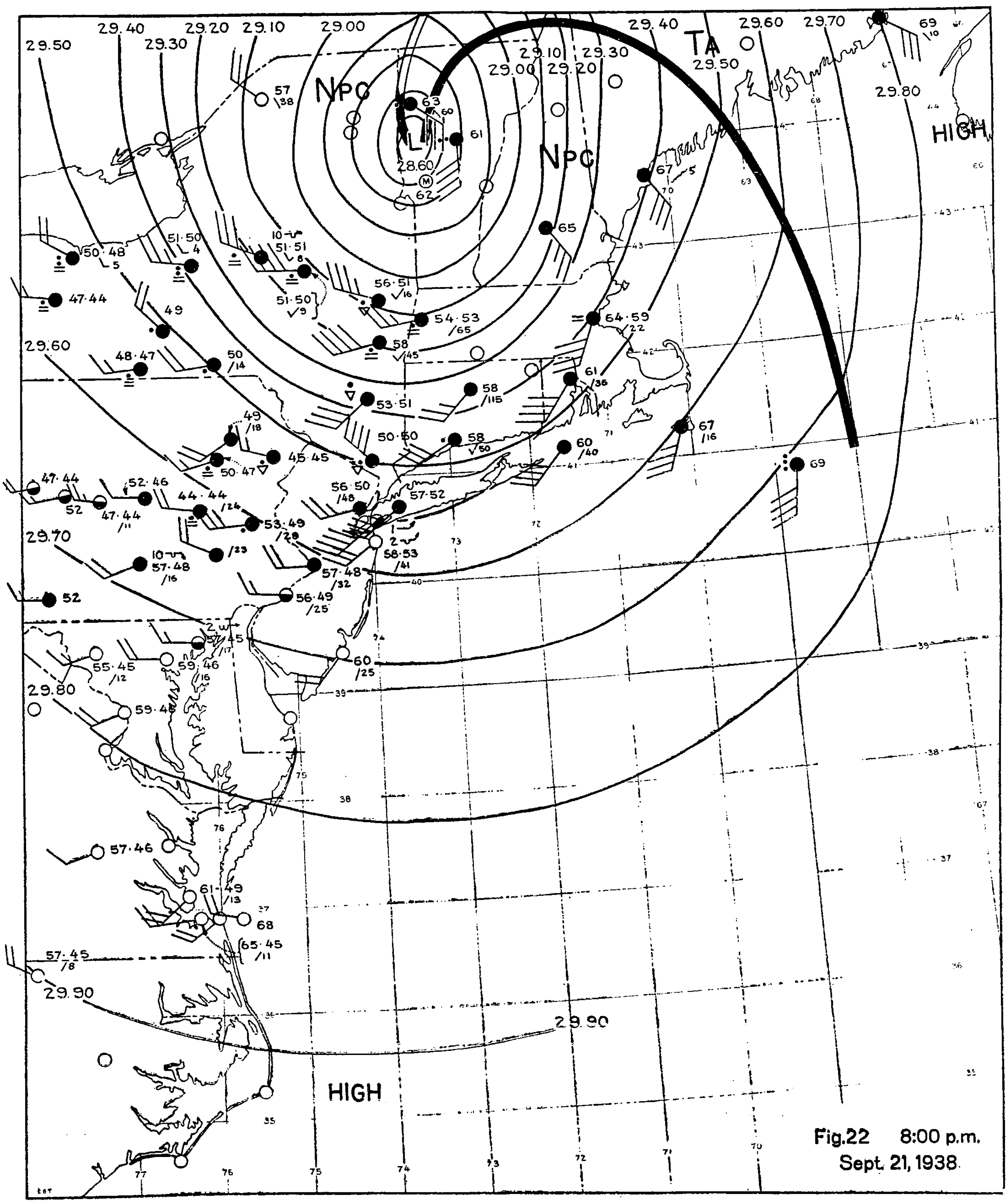


Fig. 22 8:00 p.m. Sept. 21, 1938.

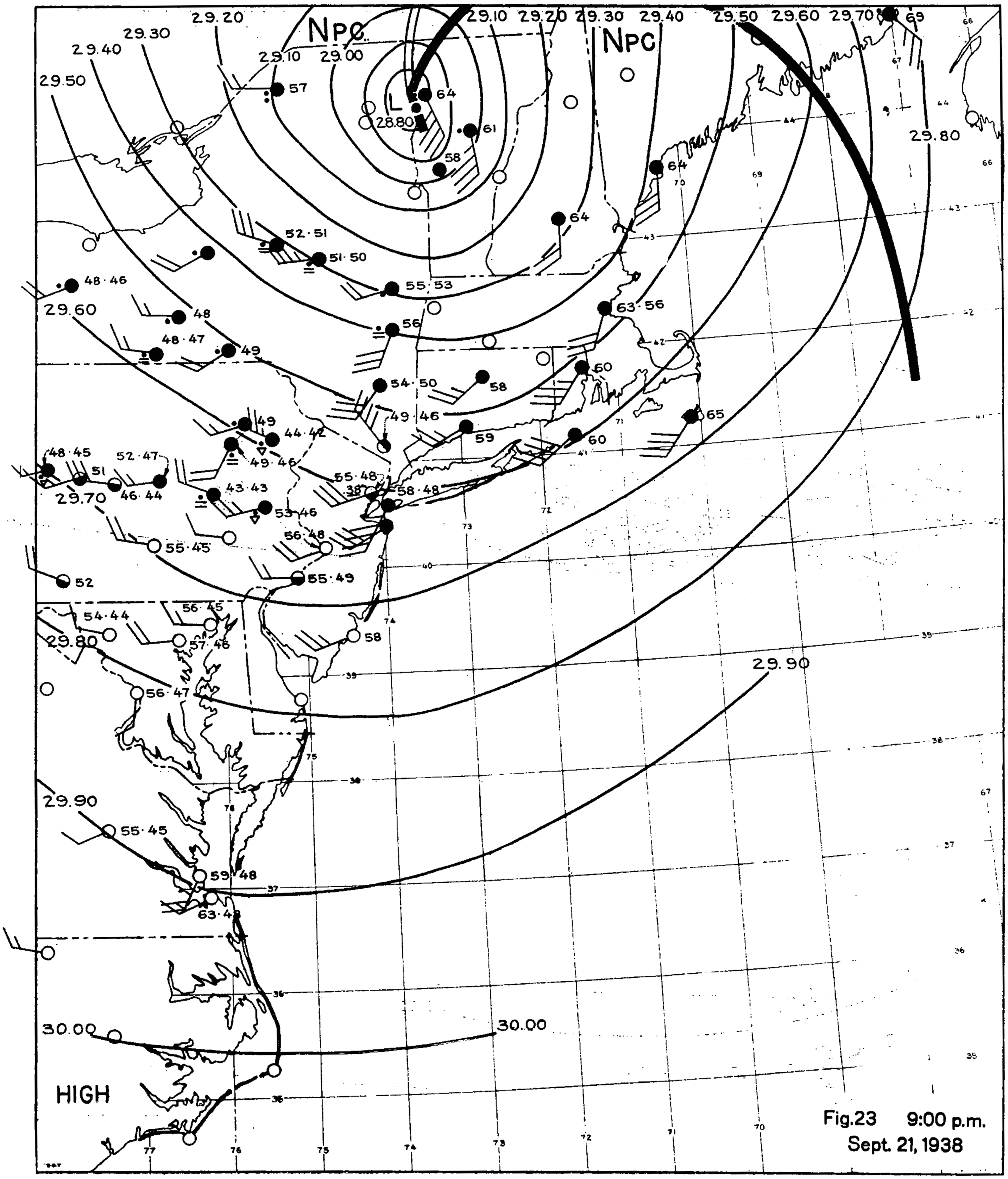


Fig. 23 9:00 p.m. Sept. 21, 1938

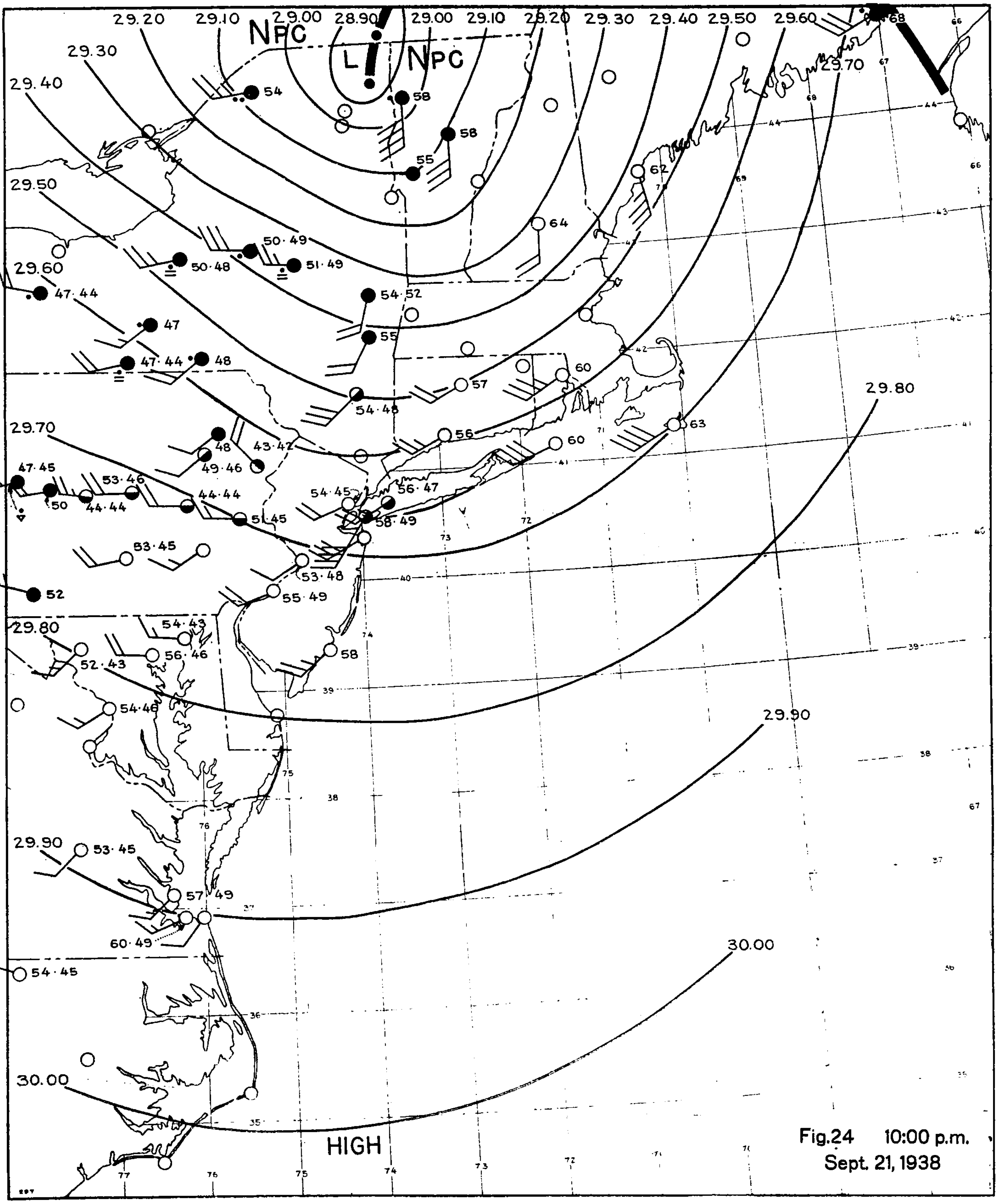


Fig.24 10:00 p.m. Sept. 21, 1938

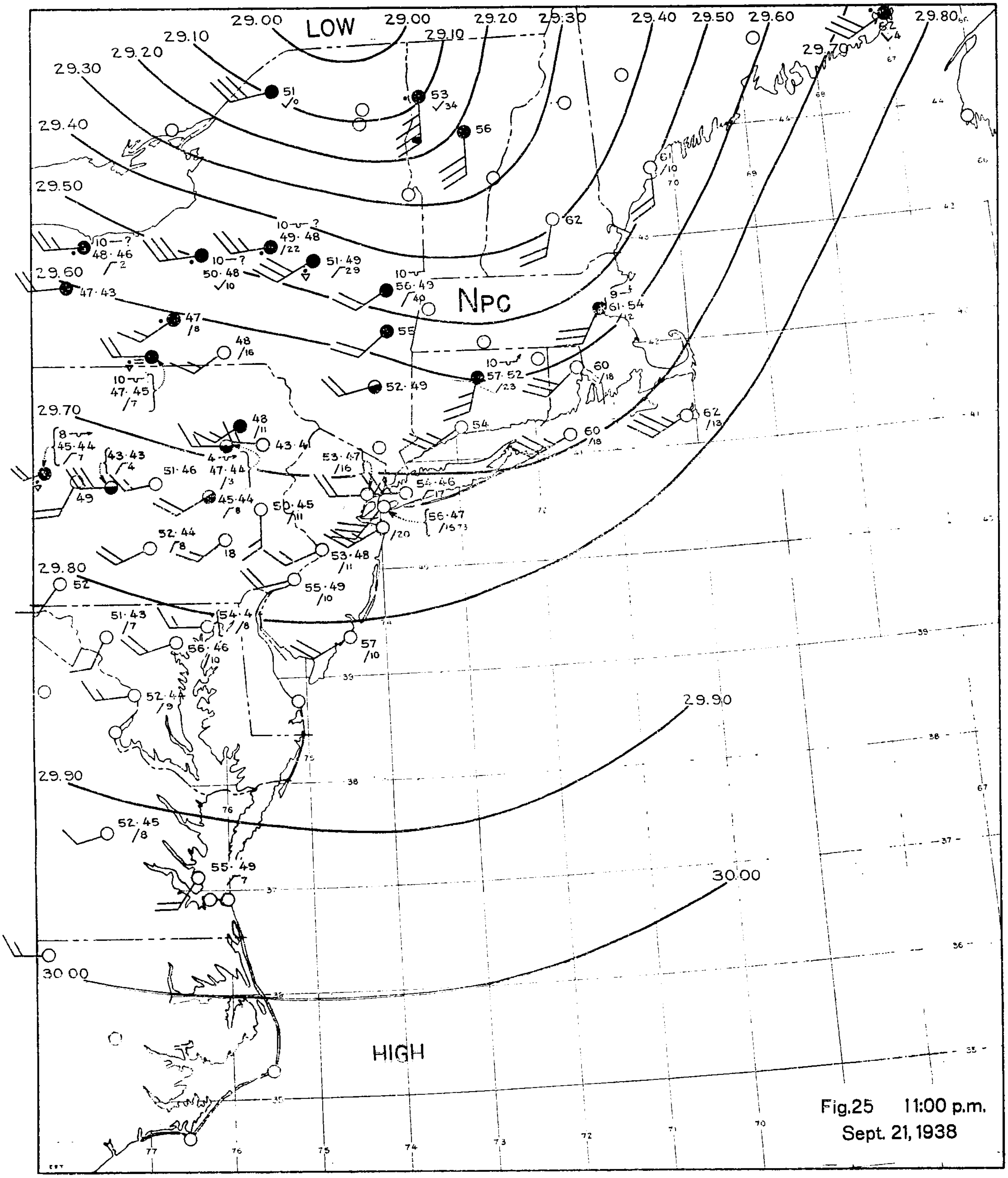


Fig.25 11:00 p.m.
Sept. 21, 1938

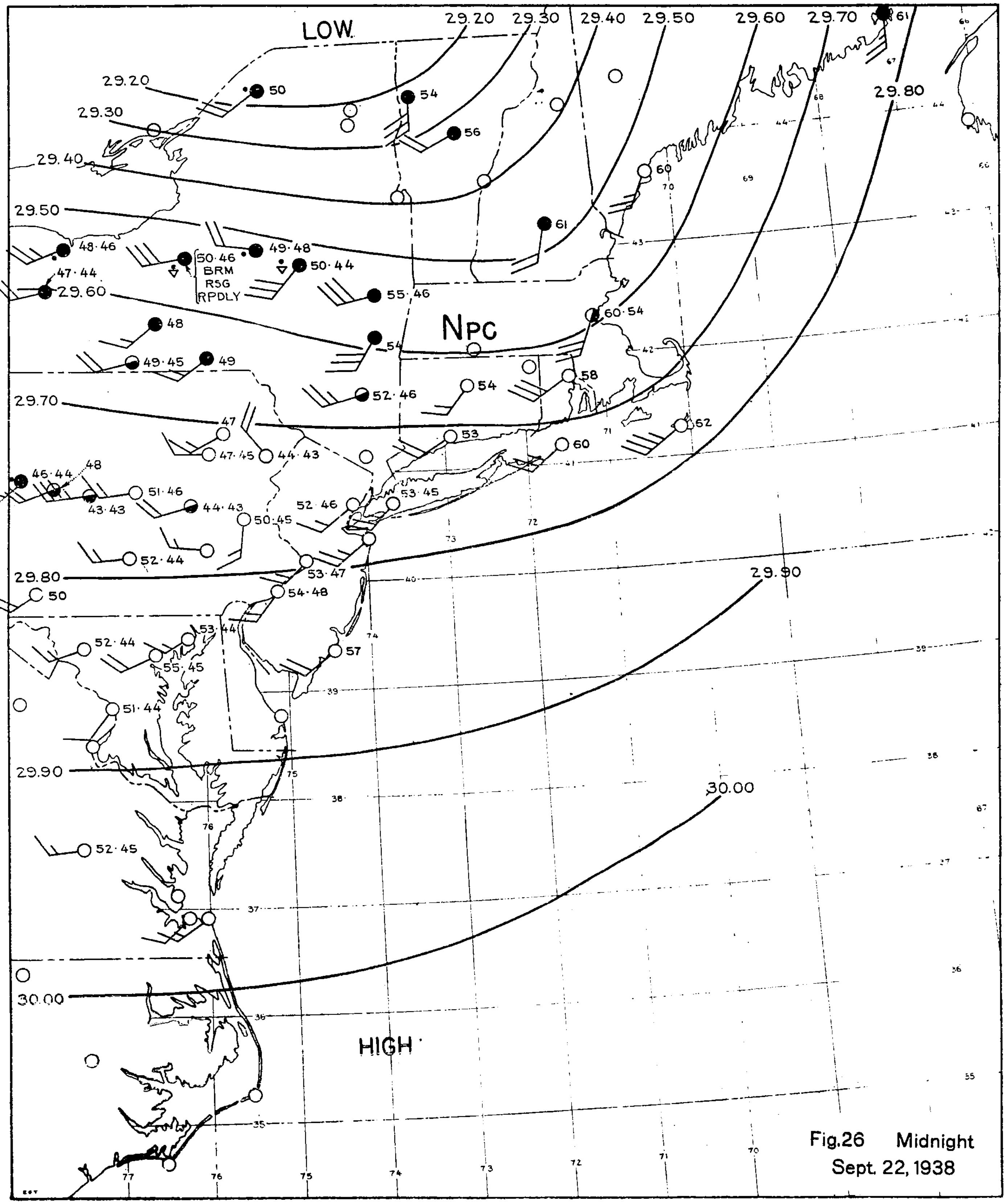


Fig. 26 Midnight Sept. 22, 1938

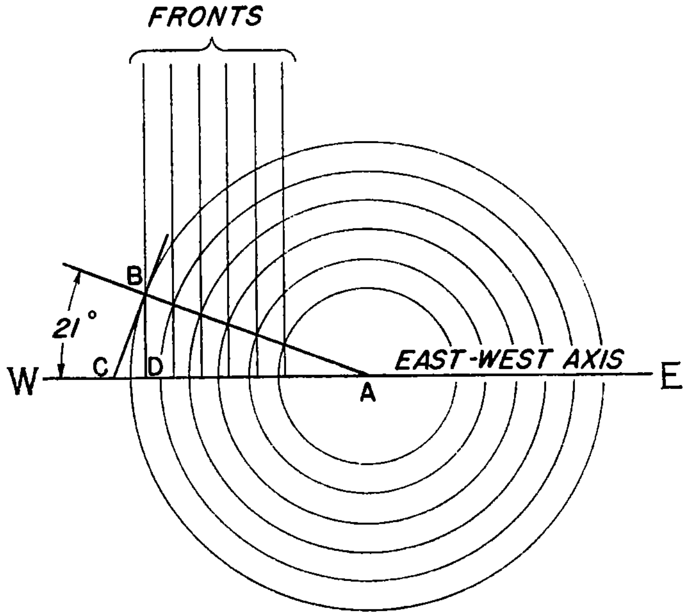


FIGURE 27. Schematic diagram of frontal movement in northwest quadrant of a LOW.

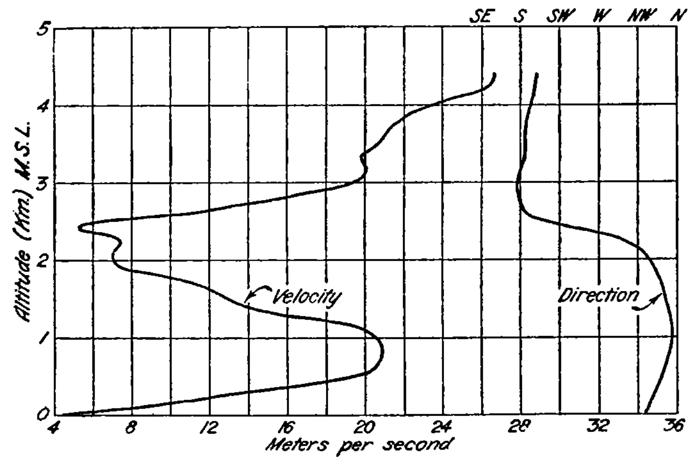


FIGURE 28. Graph of Arlington, Va., pilot balloon observation 7:52 a. m. Sept. 21, 1938.

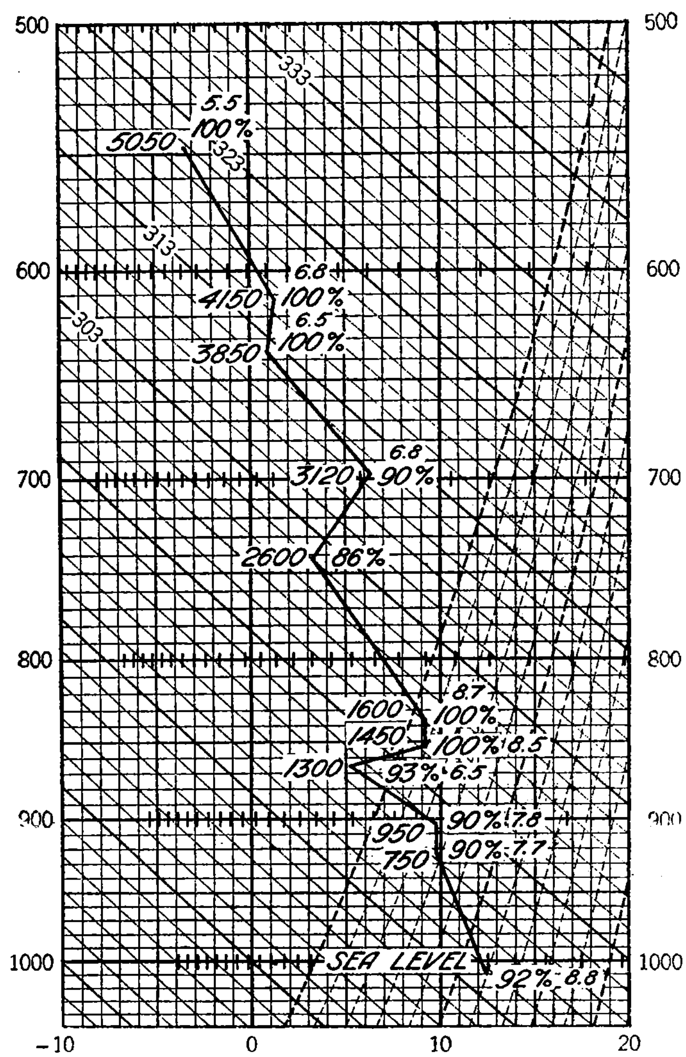


FIGURE 29. Temperature-pressure graph of the Anacostia, D. C., radiosonde observation 4 a. m. Sept. 21, 1938.

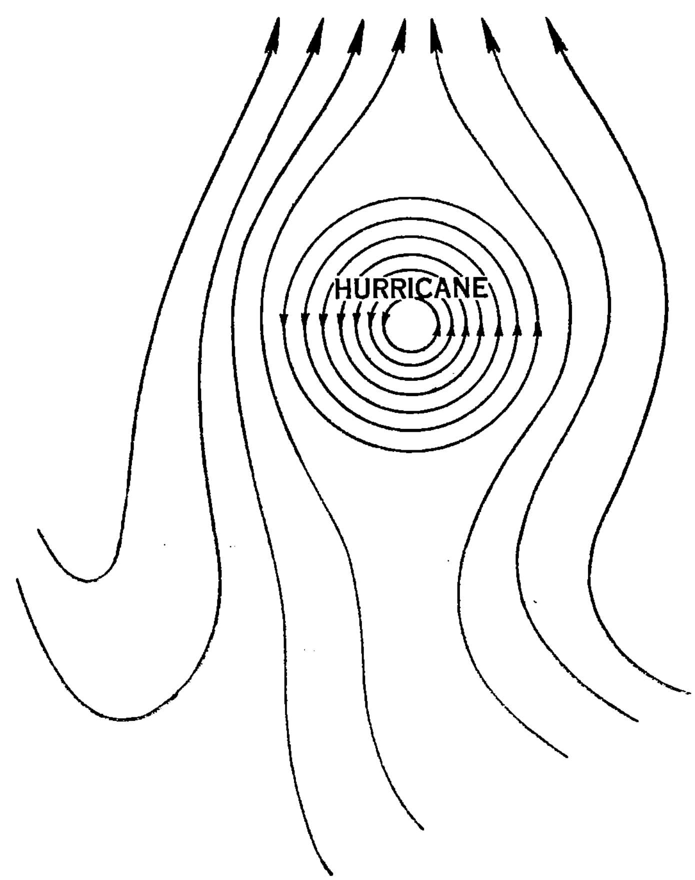


FIGURE 30. Possible stream lines at 10,000 feet altitude in the vicinity of the hurricane.

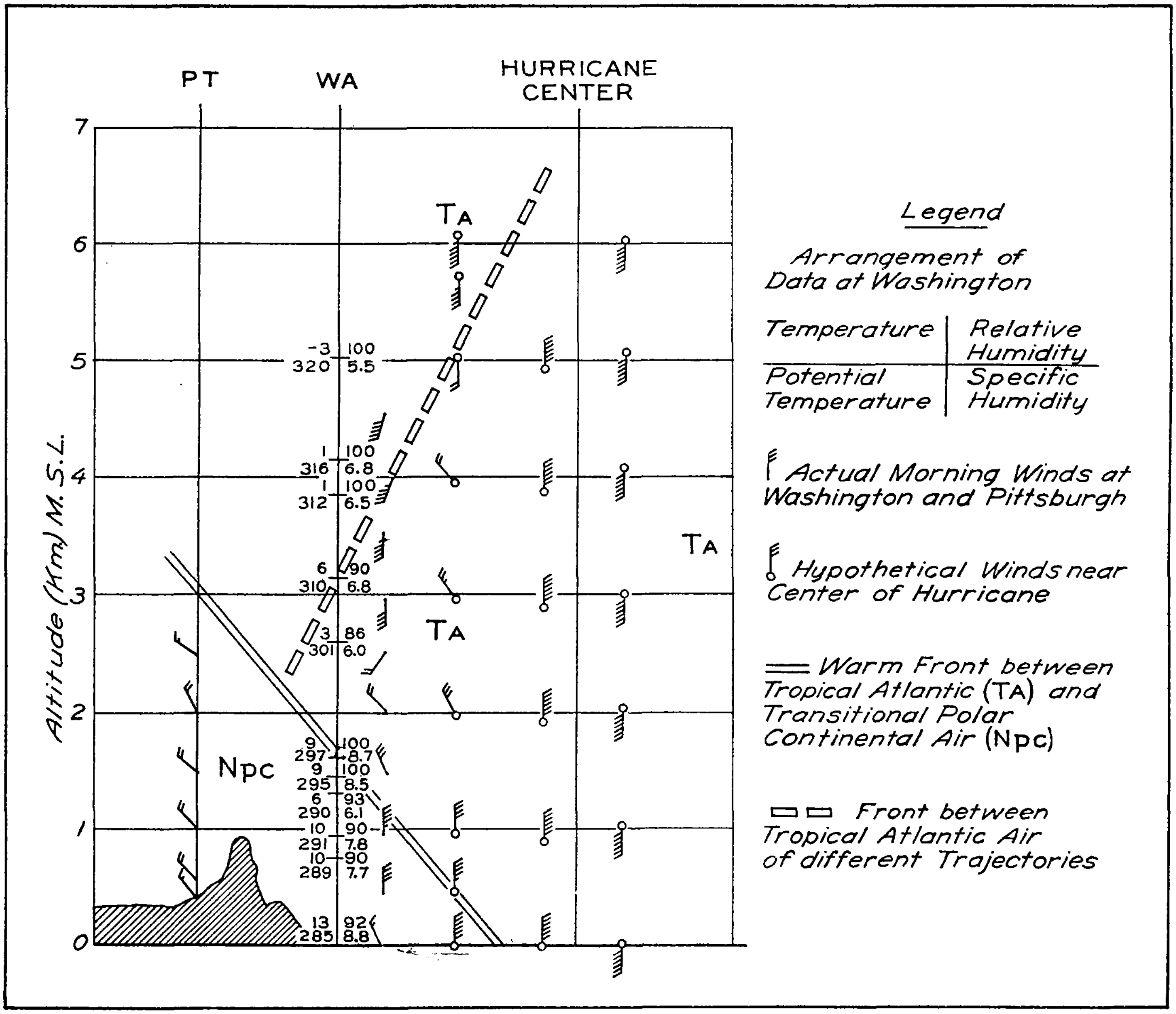


FIGURE 31. Atmospheric cross-section through Pittsburgh, Washington, and the hurricane center Sept. 21, 1938.

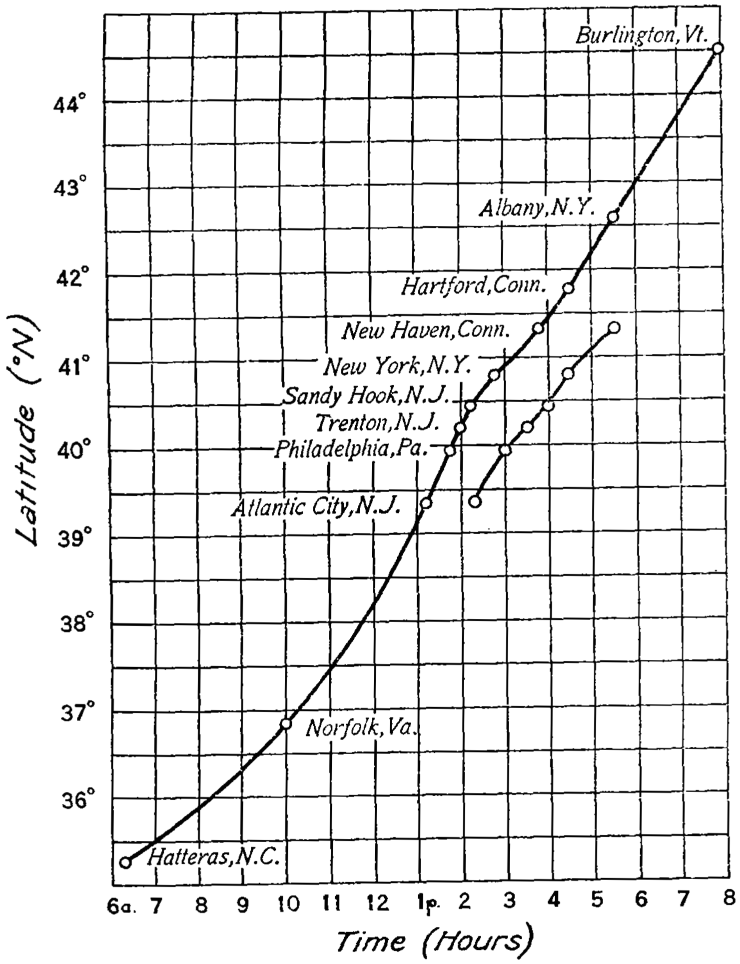


FIGURE 32. Times of the lowest pressure and of the passage of the trough at some of the stations.

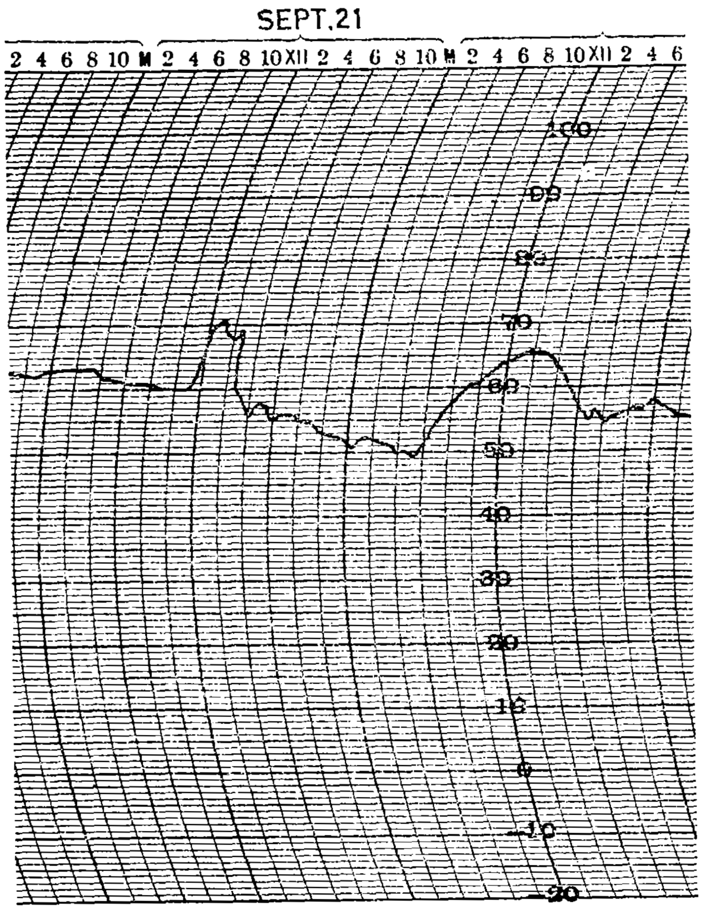


FIGURE 33. Thermograph record from Mitchel Field, N. Y., Sept. 21, 1938.

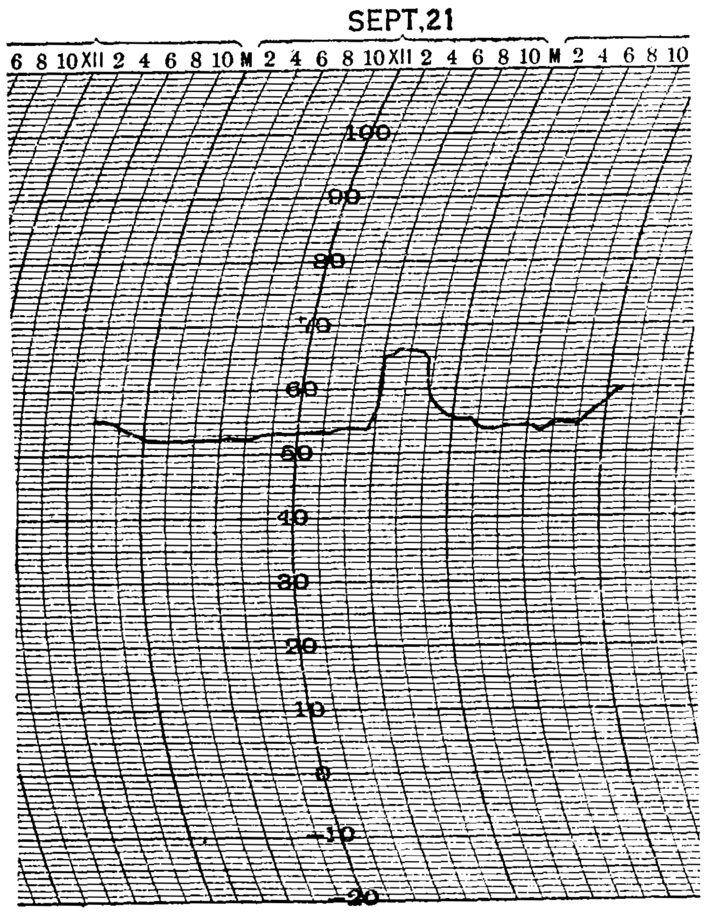


FIGURE 34. Thermograph record from Brandon, Vt., Sept. 21, 1938, through courtesy of Miss Shirley Farr (time is eastern daylight saving).

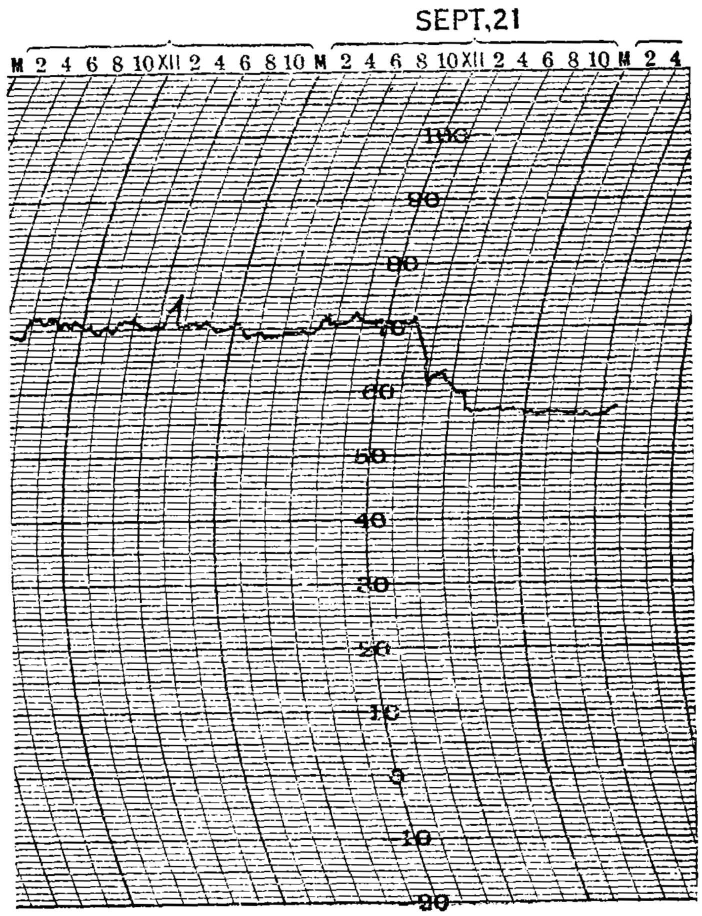


FIGURE 35. Thermograph record from Block Island, R. I., Sept. 21, 1938.

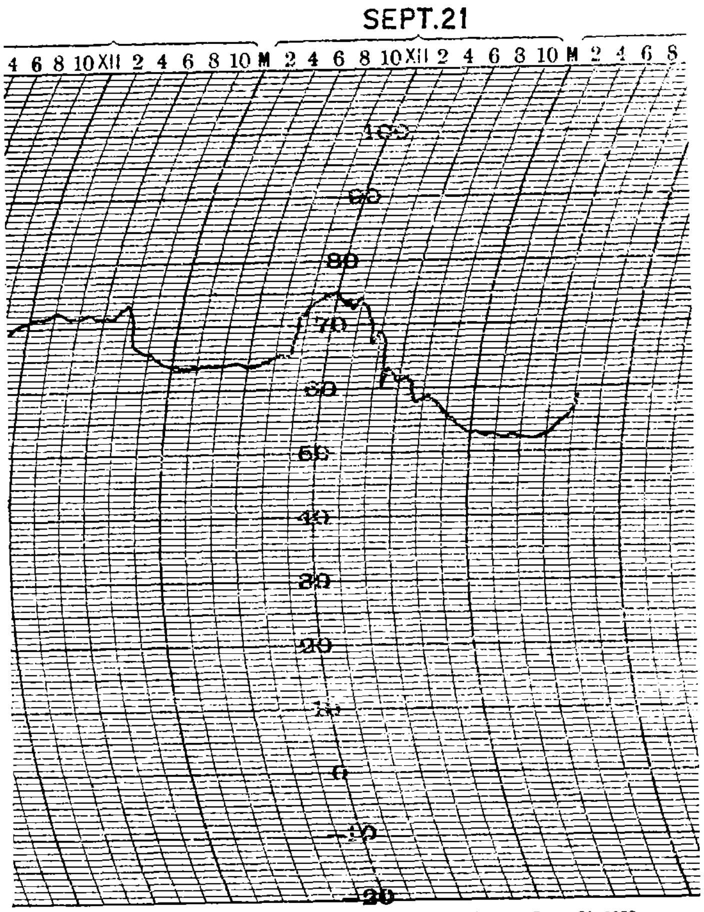


Figure 36. Thermograph record from New Haven, Conn., Sept. 21, 1938.

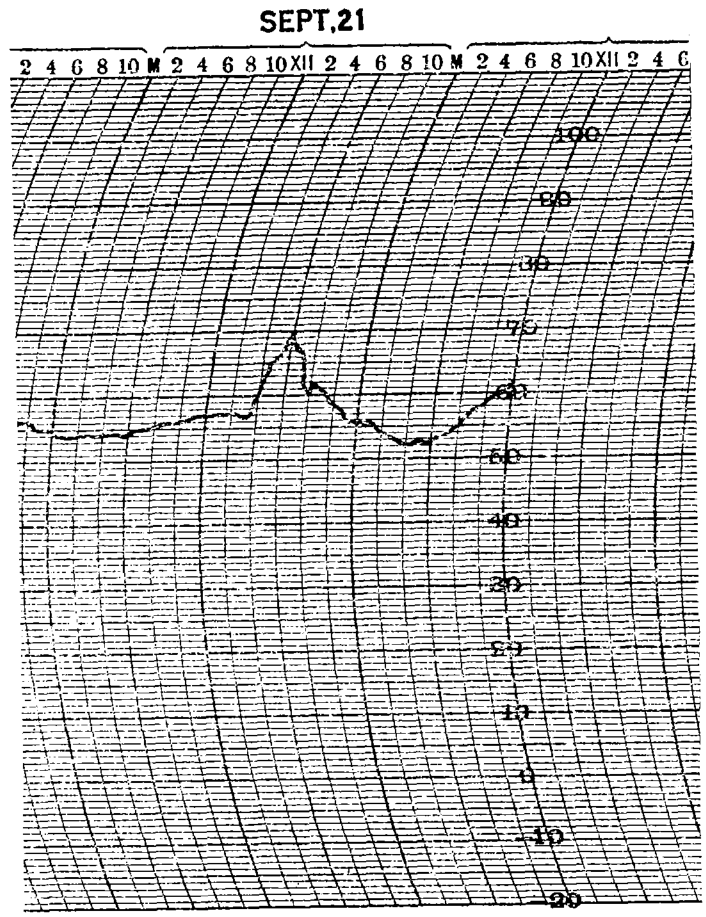


Figure 37. Thermograph record from Northfield, Vt., Sept. 21, 1938.

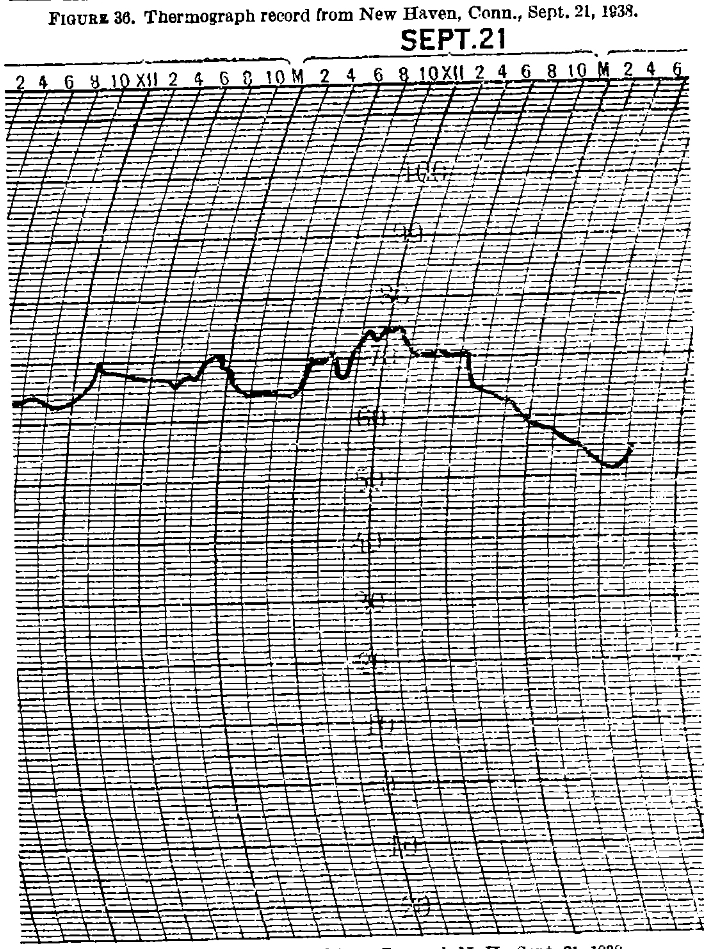


Figure 38. Thermograph record from Concord, N. H., Sept. 21, 1938.

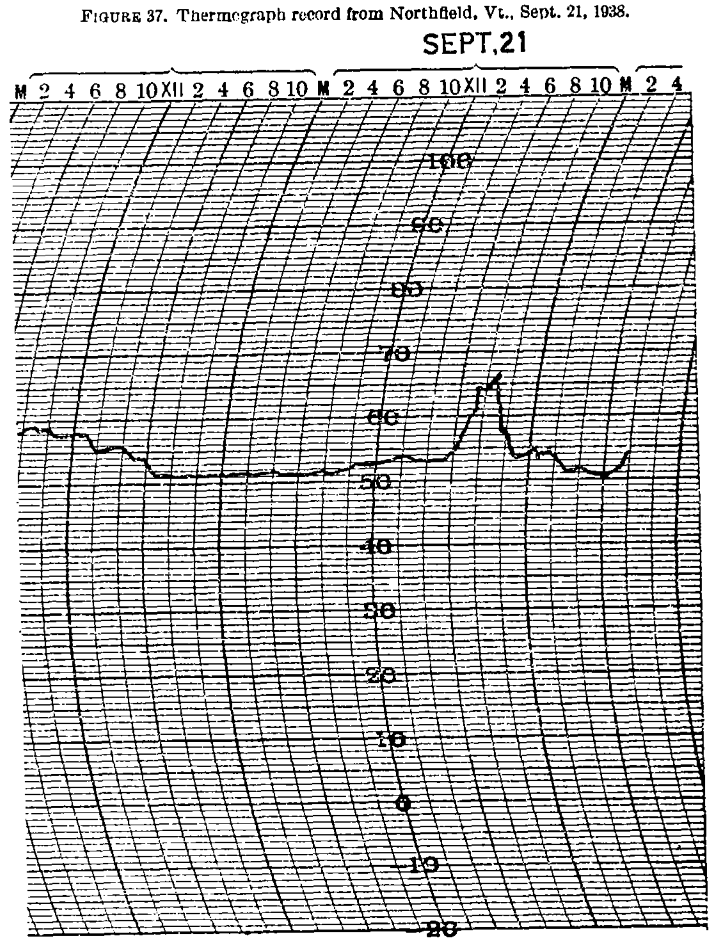


Figure 39. Thermograph record from Burlington, Vt., Sept. 21, 1938.

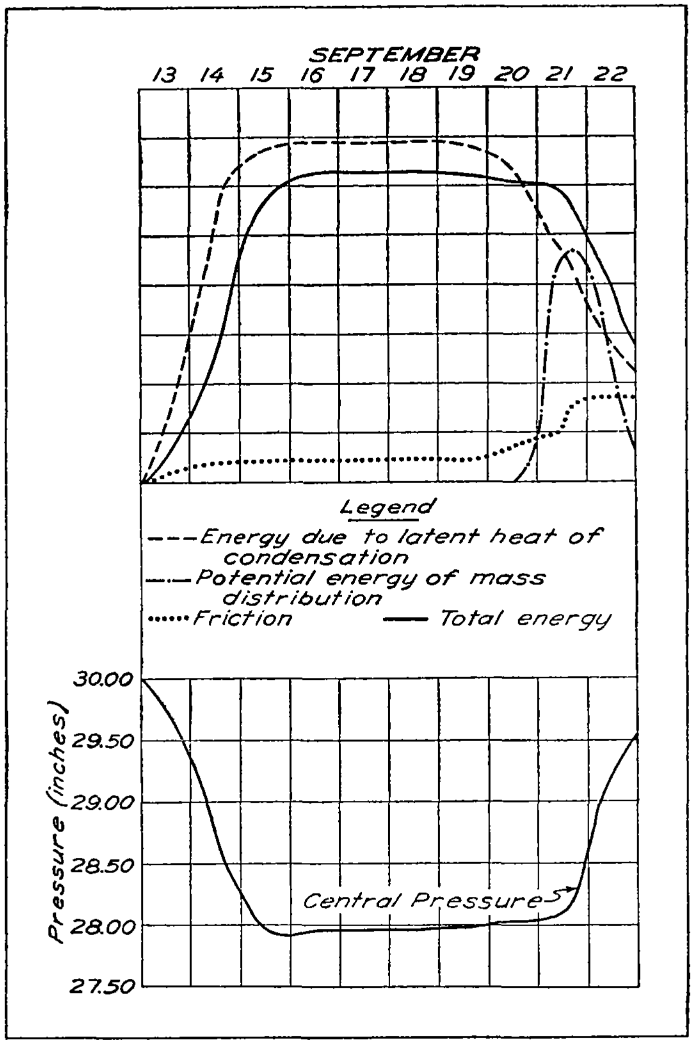


FIGURE 40. Variation in the different types of energy and in the central pressure in the hurricane.

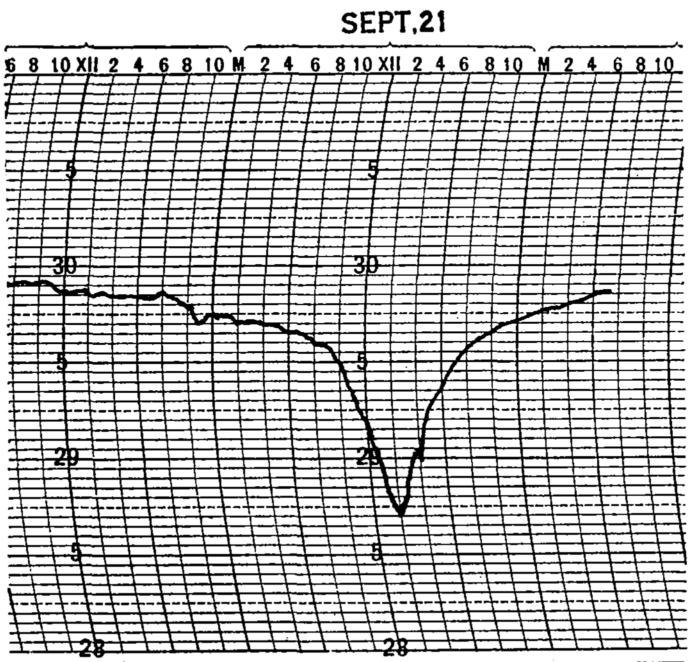


FIGURE 44. Barograph trace from Sandy Hook, N. J., Sept. 21, 1938.

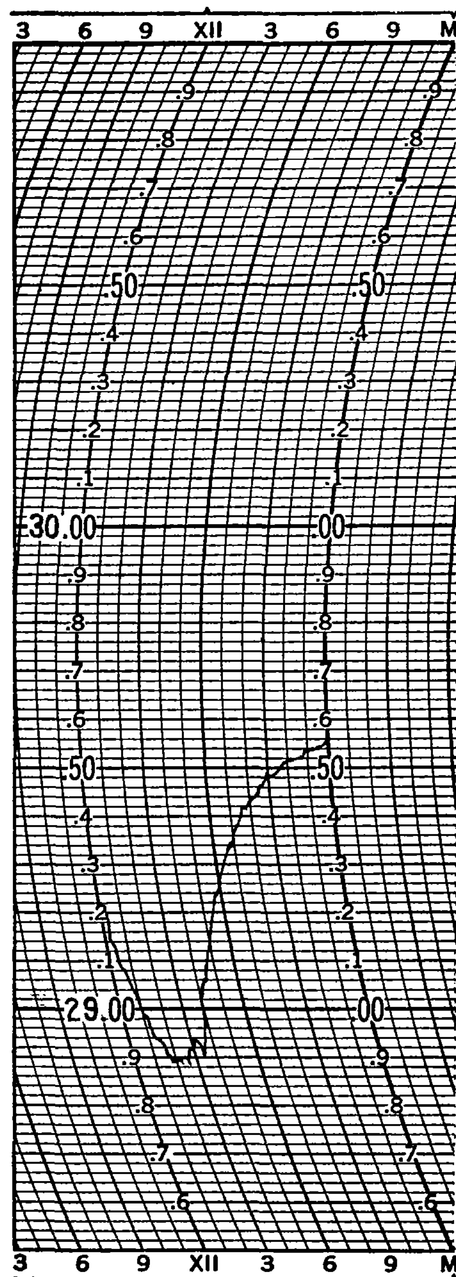


FIGURE 43. Baragraph trace from Trenton, N. J., Sept. 21, 1938.

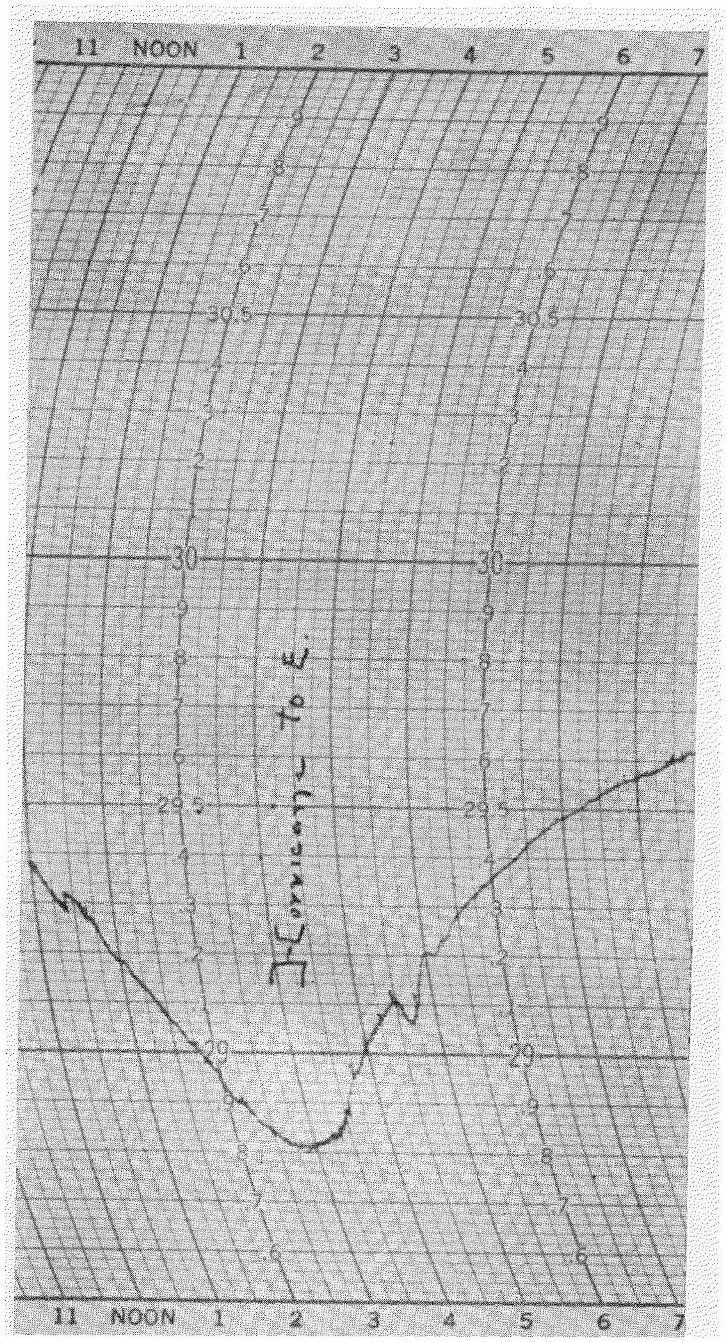


FIGURE 41.—Barograph trace from Newark, N. J., September 21, 1938, through courtesy of Eastern Airlines, Inc.

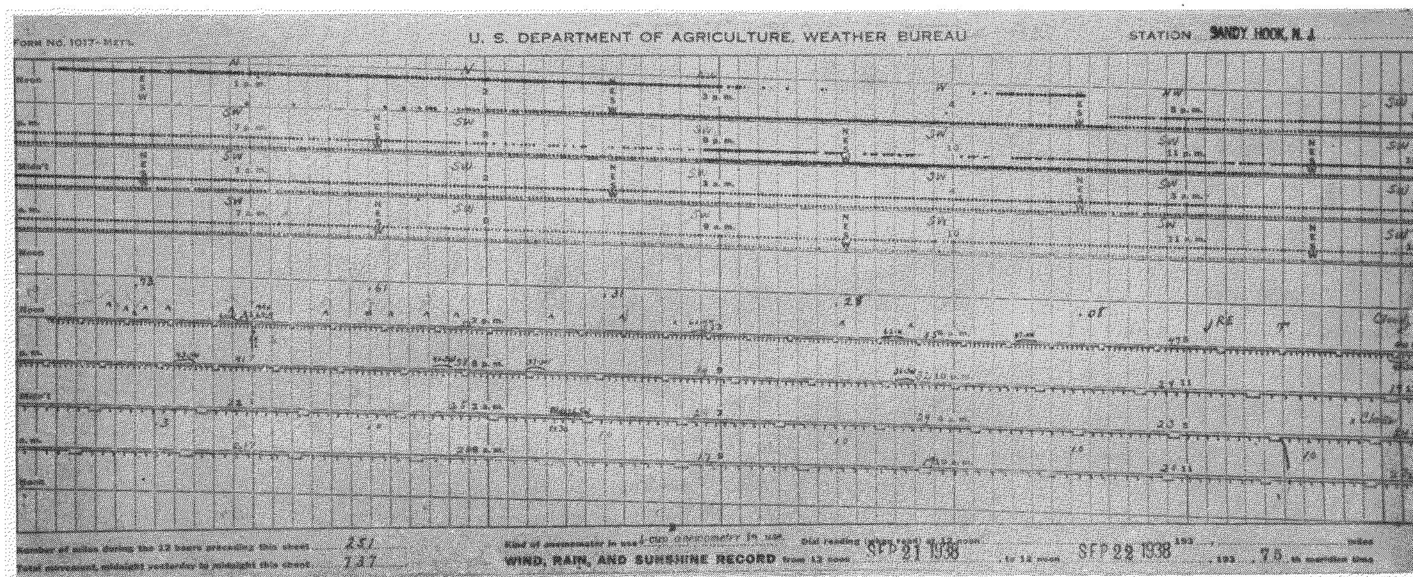
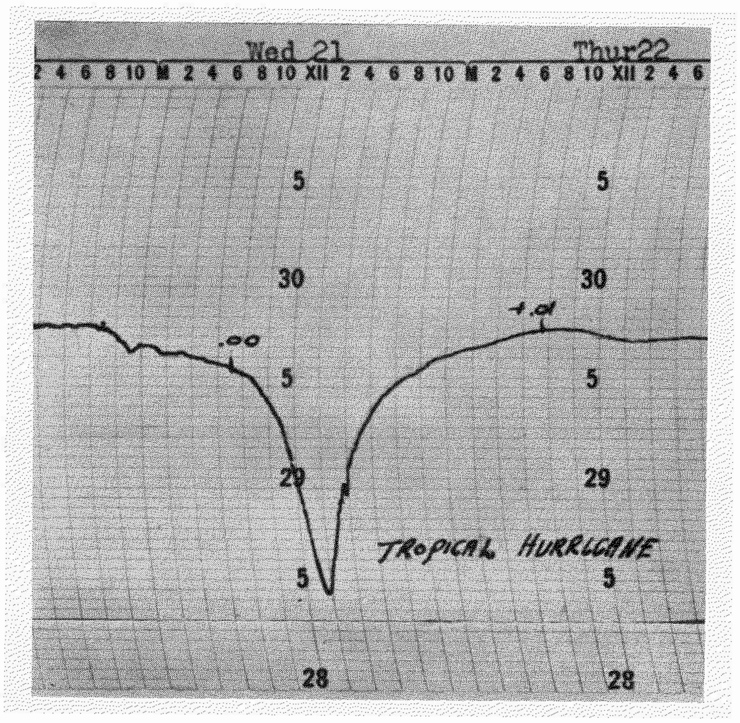


FIGURE 42.—Triple register record from Sandy Hook, N. J., September 21, 1938. The trough passage is indicated by the wind shift at 4 p. m.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TROPICAL HURRICANE
5
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28

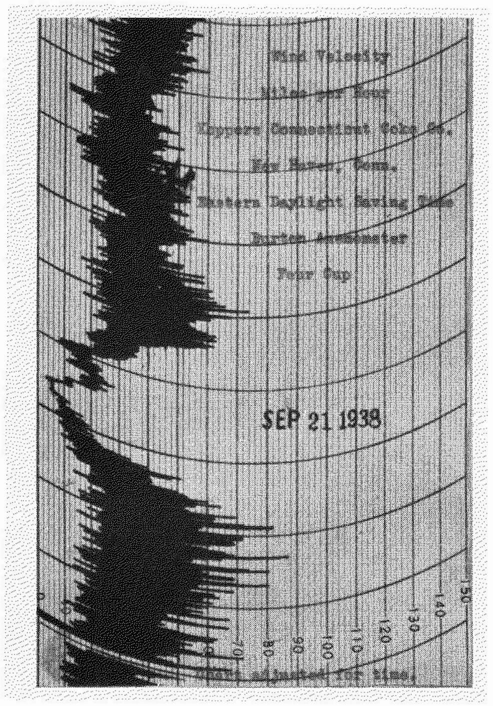

FIGURE 49.—Anemometer record from New Haven, Conn., through courtesy of Koppers Coke Co. (Burton Anemometer, four cup).

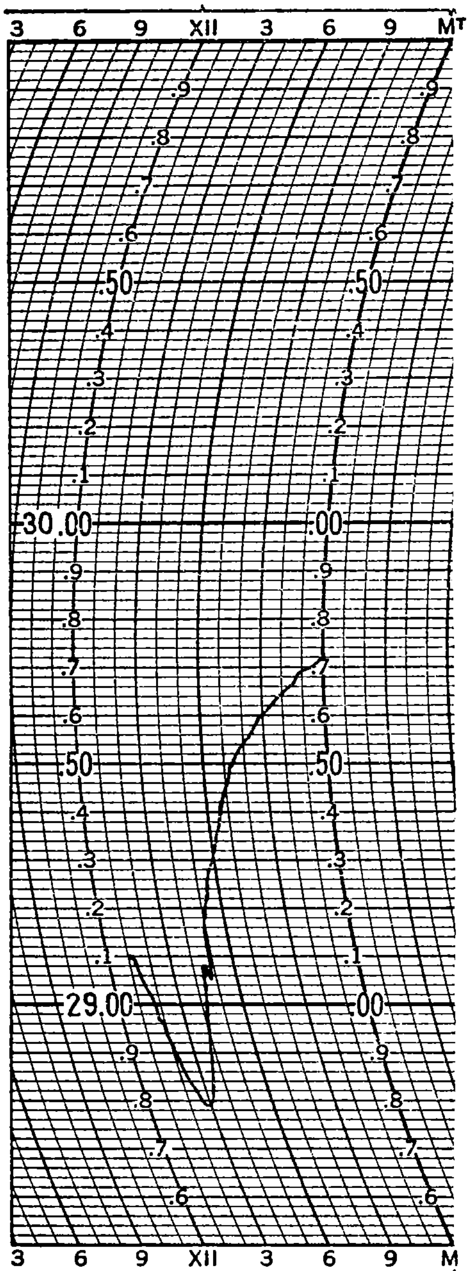

FIGURE 45. Barograph trace from Newark Airport, Newark, N. J., Sept. 21, 1938.

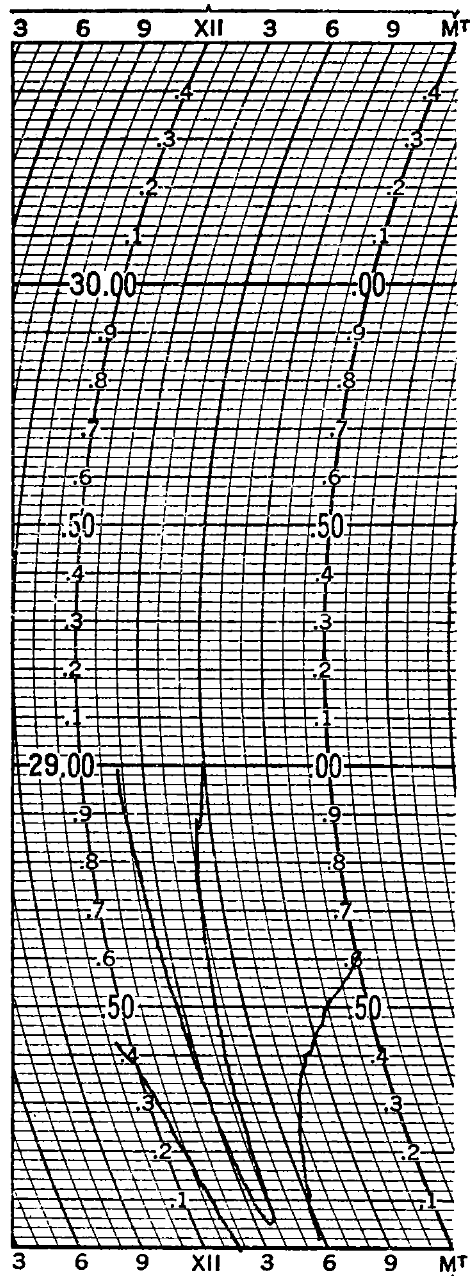

FIGURE 47. Barograph trace from New Haven Airport, New Haven, Conn., Sept. 21, 1938.

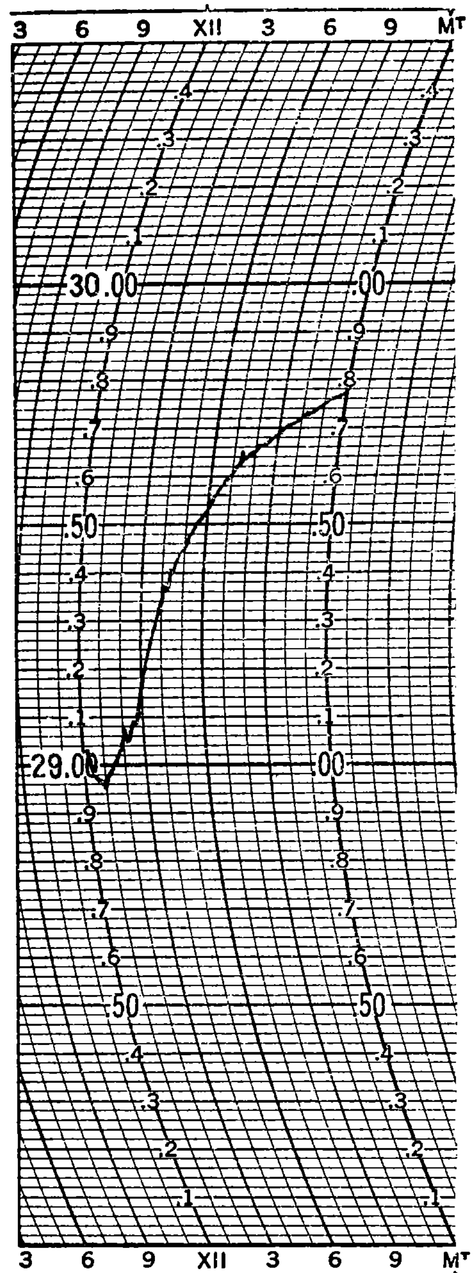

FIGURE 48. Barograph trace from Atlantic City, N. J., Sept. 21, 1938.

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